University of
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# IMPROVEMENT OF DIMENSIONAL TOLERANCE MANAGEMENT IN CONSTRUCTION

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# ABSTRACT

Tolerance-related problems are amongst the most common, recurring defects in construction projects. They are often dealt with on an ad hoc basis and at the time and place of the assembly process. The existing academic literature and the industrial guidelines provide only general recommendations for the improvement of tolerance management, and a pragmatic and holistic process for this purpose is still missing.

This research aims at developing a process to proactively identify and prevent tolerance problems at the stages preceding assembly on site. Design Science Research is the adopted methodological approach as the focus is on prescribing a solution to solve a practical problem, as well as on contributing to theory. To design a workable solution, the literature not only in construction but also in manufacturing is reviewed, empirical data is collected from three cases, fifteen tolerance problems are documented and analysed, and a detailed root cause analysis is performed for the identified tolerance problems.

The solution devised is a process, called Tolerance Management System (TMS), which has five parts, each comprising a set of steps, documents, methods and techniques implemented through a particular organisational design. The parts of TMS are: identification of tolerance requirements/risks, planning the achievement of tolerance requirements/mitigation of tolerance risks, communication of tolerance information, tolerance compliance measurement, and learning and documentation. Process standardisation and continuous improvement are two foundational elements of lean that are employed in TMS.

Two focus group meetings are conducted to evaluate whether the developed solution fulfils its aim and to refine it further. It was pinpointed during the focus group meetings that many of the TMS steps could be adopted in practice immediately to help practitioners deal with tolerances more systematically.

The research results in contributions to the theory by providing a better understanding of not only a typical but also an advanced practice of tolerance management in the construction industry, and by providing a comprehensive list of root causes of the identified tolerance problems. A contribution to both theory and practice is the developed solution, TMS, by which (a) tolerances can be taken systematically into account from project inception to completion, (b) tolerance

information can be effectively communicated amongst designers and construction trades, and (c) the conventional focus on the compliance of deviations of a single component with standards is shifted to whether sub-assemblies function properly within the specified tolerances.

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*To my Grandmother*

# LIST OF ABBREVIATIONS

ACI – American Concrete Institute

BSI – British Standards Institution

CI – Continuous Improvement

CFG – Confirmatory Focus Group

CIRIA – Construction Industry Research and Information Association

DSR – Design Science Research

EFG – Exploratory Focus Group

FG – Focus Group

GD&T – Geometric Dimensioning and Tolerancing in Construction

HRBS – Hierarchical Risk-Break Down Structure

ITP – Integrated Tolerancing Process

KC – Key Characteristic

MEWP – Mobile Elevating Work Platform

NSCS – National Structural Concrete Specification

NSSS – National Structural Steelwork Specification

PDCA – Plan-Do-Check-Act

PFC – Parallel Flange Channel

PMI – Project Management Institute

RC – Root Cause

RSS – Root Sum Square

SD – Standard Deviation

SDL – Superimposed Dead Loads

SFS – Steel Framing System

SR – Service Regularity

STM Committee – Strategic Tolerance Management Committee

TD – Total Deviation

TIN – Tolerance Interdependency Network

TMS – Tolerance Management System

TMM – Tolerance Management Meeting

TTM Committee – Tactical Tolerance Management Committee

TP – Tolerance Problem

VM – Visual Management

# CHAPTER 1: **INTRODUCTION**

## 1.1 Background

All materials and elements in the construction industry have their own dimensions, and their position is specified on drawings. In reality, however, these materials and elements cannot be exactly dimensioned and positioned as they were designed. "The accepted amount of this variation is the tolerance of the material or installed position of the material" (Ballast, 2007, p. 7). Despite of those variations, all components must fit together and meet functional and aesthetic requirements while the achievement of specified tolerances must be economic and feasible (British Standards Institution, 1990; Price, Goodier, Fouchal, & Fraser, 2019).

Variations in dimension and position of components are the result of many interacting parameters, design-related but also construction-related (Milberg & Tommelein, 2009; Vorlíček & Holický, 1989). The most important parameters are as follows:

- Most contemporary buildings are composed of a mixture of factory-made components and in situ components. This is because the construction industry is currently in a difficult transitional state, between being craft-based and industrialised (Douglas & Ransom, 2013; Koskela, 2000). This makes the construction industry unique in that tolerances range from less than a millimetre for many factory-made components to several millimetres for many in situ components (Ballast, 2007; Koskela, 2000);
- Contemporary buildings have become lighter and their structure is more flexible. They also use dissimilar materials that have different structural behaviours. Consequently, they have become more vulnerable to deflection and other types of building movements (Alexander, 2014; Alexander & Lawson, 1981). This issue results in problems in the field of tolerances and fits (British Standards Institution, 1988a).

There has been little quantitative analysis of cost, magnitude and consequences of defects associated with tolerances, called tolerance problems hereafter. Brookes (2005) concurs that more than 5 per cent of construction costs arise from the modification process due to tolerance problems. Forcada, Macarulla, Gangolells, and Casals (2016) estimate that tolerance problems are among the most common and recurring defects in Spanish housing construction and make up more than 9 per cent of the overall number of defects. Such problems can significantly affect the quality of buildings, and their economic and functional lifecycle service (Vorlíček & Holický, 1989).

It appears that tolerance problems can result in severe consequences. Tolerance problems may adversely impact functional requirement (Berg & Holicky, 1989; British Standards Institution, 1988a; Davison & Owens, 2012), safety (Berg & Holicky, 1989), serviceability, durability, constructability, the fit between components (British Standards Institution, 1990), structural stability (British Standards Institution, 1988a; Melchers & Beck, 2018; The Steel Construction Institute, 1997), aesthetics (Anderson, 1965; British Standards Institution, 1988a; The Steel Construction Institute, 1997), energy performance (Fischer, Khanzode, Reed, & Ashcraft, 2017), and compatibility with regulations (Davison & Owens, 2012). Tolerance problems can seriously increase the cost of construction and maintenance (Milberg & Tommelein, 2003b), cause delay (Zucca, Longarini, de Socio, & Migliori, 2018), and increase material wastage (Gibb, 1999). They influence customer satisfaction and are often at the centre of disputes between the consumer, contractor, supply chain, and client (American Concrete Institute, 2014; Birkeland & Westhoff, 1971). Nevertheless, fixing tolerance problems on site, which can be time-consuming, labourious and costly, is deemed acceptable in the industry because it is hard to predict how those limits can sometimes have such severe consequences (Davison & Owens, 2012).

Despite the importance of tolerances, tolerance management is sparsely addressed in academic publications (Forsythe, 2006). There are many books and published papers in the construction domain that acknowledge the importance of tolerance management but mostly consider it as a minor topic, just introducing the concepts related to tolerances (e.g. Davison & Owens, 2012; Glidden, 2001; Nawy, 2008) or presenting information (e.g. tolerance values for components) from reference documents (i.e. standards, industry guidance bulletins, and codes of practice) (Ballast, 2007; Davison & Owens, 2012). In contrast, a survey of the manufacturing literature reveals several strategies and methods for tolerance management. Given the characteristic of tolerance problems in both industries can be considered similar (Milberg, 2006), some manufacturing strategies and methods can be potentially applied to construction (Milberg, 2006; Rausch, Nahangi, Haas, & Liang, 2019).

## 1.2 Research Problem

Tolerance is a complex topic and its management has confused the construction industry and academics. There are a multitude of reasons for the current state of affairs in the field of tolerances. One of the major reasons is that tolerance is a complex amalgamation and composition of different fields of knowledge, including engineering, project management, technology, and execution techniques (Landin, 2010; Milberg, 2006; Rausch, Nahangi, Haas, & West, 2017; Shahtaheri, Rausch, West, Haas, & Nahangi, 2017).

Tolerance problems are often dealt with at the time and place of the assembly process, and the way those problems are modified to a great extent hinges on the labourer's personal experience rather than through a systematic mechanism (Milberg & Tommelein, 2009). The modifications may include cutting, using filler materials (e.g. mastic, foam, cork), scribing, and blocking-out of variations (Watt, 2009). In the worst-case scenario, after spending time and money, the component may not function as originally intended due to inept modification (Douglas & Ransom, 2013).

Despite the magnitude and impact of tolerance problems, it appears that there is little documentation and analysis of tolerance problems in the construction literature (Bradford, 2017; McCarney, 2017; Milberg, 2006). Moreover, solving a problem first requires identifying the root causes (Liker, 2004) while there is little literature available that attempts to thoroughly find the root causes of tolerance problems (Bradford, 2017; Jingmond & Ågren, 2015; Milberg, 2006).

Although standard tolerance values in the construction industry have been developed for materials such as steel and concrete, there is little input on the issue of compatibility of tolerances in connections between different materials and components (Alexander, 2014; American Concrete Institute, 2014; Ballast, 2007; Berg & Holicky, 1989; Bradford, 2017; Holbek & Anderson, 1977; Jingmond & Ågren, 2015; Milberg, 2006; Price et al., 2019; Seymour, Shammas-Toma, & Clark, 1997). This issue results in recurring tolerance problems in the industry (Forcada et al., 2016) because: (a) trades often refer to reference documents (American Concrete Institute, 2014) while compliance with a reference document does not necessarily mean that the component will fit with other components and function properly (Davison & Owens, 2012) and, (b) subcontractors are responsible only for the compliance of their own deviations with the specified tolerances and contractually they are not obligated to ensure that tolerances of other trades are compatible with their work (American Concrete Institute, 2014; Davison & Owens, 2012).

The construction industry currently is argued to lack a systematic process to effectively manage tolerances between adjoining components (e.g. avoid tolerance problems proactively) (Bradford, 2017; McCarney, 2017; Milberg & Tommelein, 2003b; Seymour et al., 1997; Vorlíček & Holický, 1989). Seymour et al. (1997) state that the process must be holistic, which means it must start from the design and continue to the completion of construction. In such a process, communication of tolerance-related information (e.g. tolerance requirements, tolerance risks) is central (Seymour et al., 1997). It is also important that potential tolerance problems, called tolerance risks hereafter, are recognised at the early stages of the project (British Standards Institution, 1990; Rausch et al., 2019).

Nevertheless, holistic management of tolerances has hardly been considered in the current construction project management literature. Existing research considers tolerances in one specific research area (e.g. tolerance analysis, tolerance coordination, tolerance communication, quality control for tolerances) (e.g. Milberg & Tommelein, 2009; Rausch et al., 2017; Rausch, Nahangi, Haas, West, & Perreault, 2016), or proposes solutions for a specific set of tolerance problems (e.g. American Concrete Institute, 2014; Bradford, 2017; Precast/Prestressed Concrete Institute, 2004). Moreover, the majority of proposed solutions are potentially costly because they require changing the measurement techniques, using off-site production, and selecting more restrictive tolerances (Landin, 2010; McCarney, 2017). Although such solutions can bring about quick improvements, they do not present a solution to avoid reoccurrence of tolerance problems (Johnsson & Meiling, 2009; Meiling, Sandberg, & Johnsson, 2014).

Furthermore, the existing methods to communicate tolerance information in construction documents (e.g. contracts, drawings, specifications) are ambiguous and increase the probability of tolerance problems (Alshawi & Underwood, 1996; Anderson, 1965; Ballast, 2007; Bradford, 2017; Frank, 2012). Finally, a major shortcoming in the existing literature on tolerances is that the data gathered in research is often based on the participants' perceptions rather than being on-site empirical data (Forsythe, 2006). These shortcomings clearly demonstrate the need for further research to address tolerance management based on the construction industry needs.

There are numerous contributions to different aspects of tolerance management in manufacturing over the decades. This shows the importance, the level of maturity and the significant developments of the topic in manufacturing (Hong & Chang, 2002; Singh, Jain, & Jain, 2009). Given that the characteristic of tolerance problems in the construction and manufacturing industries can be considered similar (Milberg, 2006), some manufacturing strategies and methods can potentially be applied to construction (Milberg, 2006; Rausch et al., 2017). There are a few novel research contributions in this field with the major emphasis on adopting tools from manufacturing into construction (e.g. Milberg, 2006; Milberg & Tommelein, 2009; Rausch et al., 2017) but no evidence exists to indicate whether these have been widely implemented within the industry. The reason for this might be that they are expressed in a difficult format for the industry, and even for academics, to understand, interpret and apply as they have sometimes been taken from manufacturing without any refinement towards a more relevant application (Talebi, Koskela, Shelbourn, & Tzortzopoulos, 2016). It should be noted that the knowledge transfer from manufacturing into construction should be treated with caution because the level of maturity of processes and practices in manufacturing and construction is different (Kagioglou, Cooper, Aouad, & Sexton, 2000). This issue, per se, calls for a realistic effort to apply techniques adopted and refined from manufacturing in construction to improve tolerance management performance.

All in all, currently, tolerance management within the construction industry is addressed on an ad hoc basis. Research work is needed when there is no adequate and systematised solution for a given problem (Dresch, Lacerda, & Antunes Jr, 2015). Therefore, there is a need for research work to develop a better approach towards tolerance management (Anderson, 1965; Ballast, 2007; Bradford, 2017; Forsythe, 2006; Milberg, 2006; Shahtaheri et al., 2017).

## 1.3 Research Aim and Objectives

This research aims to develop a systematic and holistic system, called Tolerance Management System (TMS), to proactively identify, analyse, and mitigate tolerance problems at stages preceding construction on site. This should lead to an improvement of the project performance in terms of time, cost, and quality.

The objectives of the research are defined as follows:

- **To obtain** a comprehensive understanding of the current problems and practices of tolerance management in design and construction; especially to understand existing mechanism used to manage tolerances, e.g. how tolerances are specified in the industry, and how the compliance of deviations with the specified tolerances is verified; to understand what currently interrupts that mechanism, e.g. what tolerance problems exist; and to understand the root causes of tolerance problems;

- **To develop** a solution based on the literature review and findings during empirical studies to incorporate tolerances into design and effectively control them during construction with the goal of tackling the root causes of tolerance problems;
- **To evaluate** the appropriateness of the solution, TMS, explore factors that enable and impede its successful implementation, and refine the solution.

## 1.4 Research Method Outline

Design Science Research (DSR) is adopted in this study. DSR is the most appropriate research approach, when the research focus is on designing an artefact and prescribing a solution to solve a problem in the real world, and also contributing to theory (Hevner, March, Park, & Ram, 2004; van Aken, 2005; Walls, Widmeyer, & El Sawy, 1992). Tolerance is a problem in practice while there is insufficient academic knowledge about ways to improve tolerance management (Alshawi & Underwood, 1996; Bradford, 2017; McCarney, 2017; Milberg, 2006; Shahtaheri et al., 2017). The aim of this research is to design a solution to solve a relevant practical problem (i.e. improving tolerance management) which has a potential for theoretical contribution. Hence, DSR seems the most appropriate research approach. Further details about the selected research method, justification behind its selection and the steps undertaken to carry out the research can be found in Chapter 3.

After reviewing processes to undertake DSR proposed by Walls et al. (1992), Kasanen, Lukka, and Siitonen (1993), Alturki, Gable G, and Bandara (2011), van Aken, Berends, and Van der Bij (2012), and Vaishnavi and Kuechler (2015), the following steps are taken in this research to fulfil the aim and objectives: (a) problem definition, (b) awareness of problem, (c) suggestion of solution, (d) development of solution, (e) evaluation, and (f) conclusion. Figure 1-1 shows how the objectives fit together and the DSR steps taken in this research.

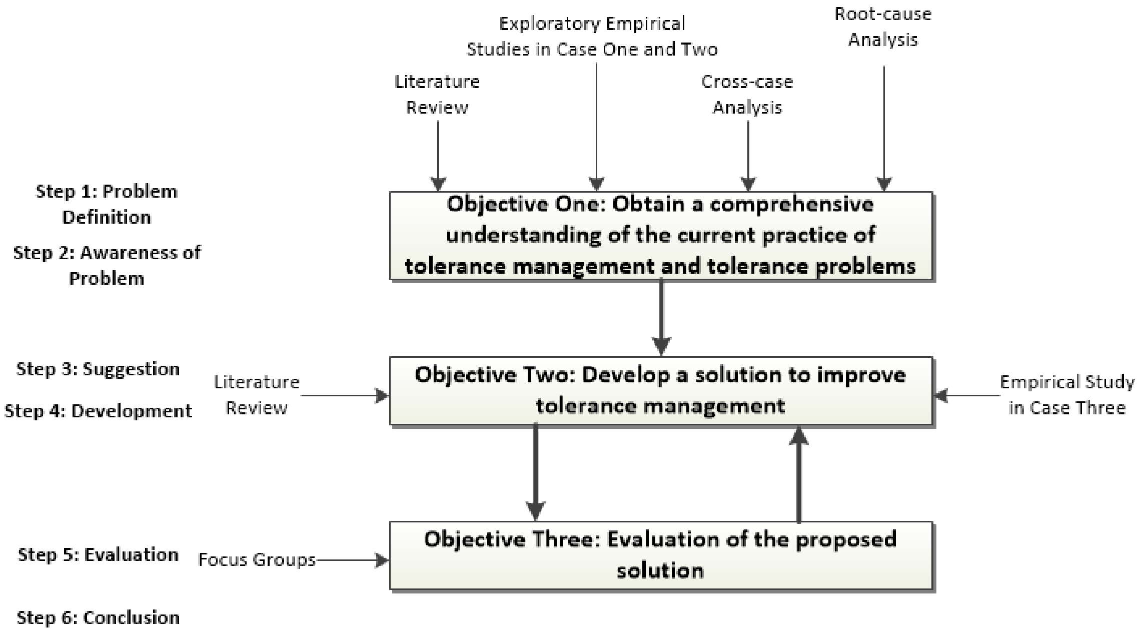



**Figure 1-1. Outlines of research objectives and the DSR steps**

The first step starts with a review of the literature to characterise the term tolerance management in construction to identify the foremost subjects in the field of tolerances, and to recognise the areas of concern from the preceding researchers' point of view. The literature helped the researcher to understand the underlying need of the industry.

In the second step, exploratory studies were conducted with two construction companies to better understand activities related to tolerance management practised during design and construction. Fifteen tolerance problems were identified in these two cases, fifteen semi-structured interviews were carried out, and documents (e.g. drawings, surveying results, specifications, quality check sheets) were reviewed. The review of the literature continued with a greater emphasis on the literature related to root causes of tolerance problems. The cross-case analysis as well as root cause analysis of the identified tolerance problems were performed. After this step, the researcher could state the problem with clarity and define the research scope.

In the third step, the preliminary solution to proactively identify and minimise tolerance problems was proposed. Reports including recommendations to improve the practice of the general contractors of two cases for similar upcoming projects were provided in the form of confidential reports.

The fourth step involved the engagement with an engineering consultancy to understand the state-of-the-art in the industry in the realm of tolerance management. This broadened the understanding of the problem and potential solutions. The focus of the review of the literature in this step was on the literature, which can directly influence the development of the solution and included the literature in construction, mechanical engineering and manufacturing. This step led to further development of the solution.

The fifth and sixth steps involved the partial evaluation of the proposed solution through two focus groups, as well as discussions regarding contribution to theory and practice.

## 1.5 Research Scope

This research has a relatively broad focus as it includes early stages of the project through to completion, more specifically, from stage two of the Royal Institute of British Architects (RIBA) Plan of Work up to stage five (Royal Institute of British Architects, 2013). It contains details of the collective-decision making and communication during all these four stages. Also, it includes incorporation of tolerances into design and other contractual documents at stages three (i.e. developed design) and four (i.e. technical design) of the RIBA, and it includes quality control at stage five of the RIBA. Hence, it provides details of the tolerances at the design stage, tolerances in practice, and the control of tolerances.

To keep the research and analysis within affordable limits, the focus of this research is on buildings with steel and concrete structural frames. The results of this study is not intended to be applied to timber construction, prefabrication, modularisation, and construction of special structures, such as high-rise buildings and pre-stressed circular structures.

The research does not directly deal with tolerances of components during the manufacturing. However, the decisions made during the proposed process should be used in the manufacturing.

The research is mainly concerned with tolerances in connections and sub-assemblies rather than a single component. The research does not generate any mathematical and engineering methods to specify optimal tolerance values, rather it modifies and standardises existing guidance and practice, and relies on collective decision-making. It tackles both inherent and induced sources of variations.

The proposed solution is developed from the general contractors' point of view. It is assumed that general contractors, or any other party consulting general contractors, are the primary users of the system (i.e. TMS). The research involves four domains of knowledge: construction project management, structural engineering, quality management, and mechanical engineering.

## 1.6 Thesis Outline

***Chapter 1 – Introduction***: This chapter provides the research background; defines the research problem related to tolerances in construction; describes the research scope, objectives, and methodological approach. It gives background information about the author and outlines the thesis structure.

***Chapter 2 – Literature Review***: This chapter presents the literature synthesis, focusing on the relevant literature around finding solutions to tolerance problems. This chapter not only reviews the literature in construction, but also in manufacturing.

***Chapter 3 – Research Method***: This chapter describes the selected research method. It justifies methodological choices and describes the research design.

***Chapter 4 – Empirical Studies***: This chapter describes the activities and documents that are used for the management of tolerances in two empirical studies, and provides an understanding of the existing activities related to tolerance management. It includes the tolerance problems identified through observations in two cases. Afterwards, the cross-case analysis for the first two cases is presented***.***

***Chapter 5 – Root Causes of Tolerance Problems***: This chapter analyses the root causes of tolerance problems described in the previous chapter. The aim of this chapter is to establish a thorough understanding of the issues in the field of tolerance management.

***Chapter 6 – Tolerance Management System***: This chapter first provides a background to the developed solution, called TMS. The steps of TMS are then presented in detail along with examples to demonstrate how the solution can cope with tolerance problems proactively.

***Chapter 7 – Evaluation of Tolerance Management System***: This chapter presents the evaluation of the TMS carried out by two focus groups.

***Chapter 8 – Conclusion***: This chapter examines the achievement of the research aim and objectives. It presents a synthesis of the discussions made throughout the research, contribution to theory and practice, conclusion, and future research to develop TMS further.

# CHAPTER 2: **LITERATURE REVIEW**

In this chapter, first, the importance of tolerances in construction is delineated. Second, the key concepts related to tolerances are presented. Next, the processes and recommendations proposed to improve tolerance management, not only in construction but also in manufacturing, are reviewed. Following this, root causes of tolerance problems in construction are analysed. After examining tolerance management in construction and manufacturing, and the root causes of tolerance problems, the theoretical background underpinning the proposed artefact in this research is presented. Lastly, terms used in manufacturing for tolerance management are reviewed and refined to be adopted for tolerance management in construction. This chapter helps problem definition and awareness of problem, especially through exploring the root causes of tolerance problems. It then contributes to the development of the solution through reviewing tolerance-related concepts in construction and manufacturing.

## 2.1 Importance of Tolerances in Construction

One may argue "why investigate tolerances? are they really important?". In fact, there are many reasons that tolerances are important and should not be overlooked. Some of these reasons are explained in the following.

Function: The constructed building has to function as intended in the design. Dimensional and geometric variations may adversely impact the function of the completed building (British Standards Institution, 1988a). For instance, if the permitted variations in the space between two components are encroached, the desired functionality from the interface may not be obtained (e.g. the building structure may conflict with door or window openings, walls, etc.) (Davison & Owens, 2012).

**Appearance:** Variations in size, position and form of components can adversely impact the appearance of a building (Anderson, 1965; British Standards Institution, 1988a; The Steel Construction Institute, 1997).

**Stability:** If a building structure does not adhere to the permitted variations, the impact of forces applied to the structure may become greater than what the structure is designed to withstand and as a result, the structure may fail to function or may collapse (British Standards Institution, 1988a; Precast/Prestressed Concrete Institute, 2004; The Steel Construction Institute, 1997).

**Construction flow**: Fixing defects associated with tolerance problems may interrupt the workflow (Milberg, 2006).

**Economic**: The interruption of workflow due to tolerance problems, and the modifications needed to solve those problems, result in an economical loss (Anderson, 1965; Precast/Prestressed Concrete Institute, 2004).

**Structural integrity**: Decisions about the modifications needed to correct tolerance problems can be difficult to make. This is because often the decisions are made when work has been already completed and the decisions have to account for the structural integrity (Melchers & Beck, 2018). For example, in concrete structures, if the final finish does not satisfy the tolerance requirements and it must be modified, because it is highly visible, one solution is to grind surfaces. However, the grinding of the surfaces must be very shallow to avoid reducing the cover needed for concrete slabs (Graham & Lindholm, 1978).

**Design intent**: In manufacturing, the conversion of a good design into a good product is a matter of keeping the dimensional and geometric variation within tolerances predetermined at the design stage. The acceptability of a product depends on whether its variations in size and geometry falls within the limits; thus, the bridge between design and production is tolerance (Gilson, 1951; Zhang, 1997). Similarly, tolerances are the connecting point between design and construction, because without specifying tolerances it is not clear whether components, assemblies or buildings as a whole meet the design intent in terms of accuracy.

**Site boundaries**: The boundaries of a site should not exceed the permitted sizes for legal reasons. The boundaries can be adversely affected due to inclination of tall buildings or outer faces (British Standards Institution, 1988a; Davison & Owens, 2012; Precast/Prestressed Concrete Institute, 2004).

## 2.2 Tolerance Terminology

The most common terms relating to tolerances are listed and defined in Table 2-1.

**Table 2-1. The most common terms in tolerance management and corresponding definitions**

| TERM | DEFINITION |
|---|---|
| Variation | When the dimension (i.e. size) and geometry (i.e. form) of a component vary from the targeted dimensional and geometric values in the design (Creveling, 1997; Thornton, 2004). |
| Deviation | The difference between an actual measured value and the specified value is a deviation. The deviation is expressed vectorially (British Standards Institution, 2013). The difference between the variation and the deviation is that the variation describes the total of all constituent deviations (Bonshor & Eldridge, 1974). |
| Tolerance | All components in the construction industry have their own dimensions. Also, their position on the drawings are specified. In reality, however, these components cannot be exactly dimensioned and positioned as they were designed. "The accepted amount of this variation is the tolerance of the material or installed position of the material" (Ballast, 2007, p. 10). In other words, the tolerance can be defined as a permitted variation from a basic dimension in the width or length of a member (Precast/Prestressed Concrete Institute, 2004), and the permitted variation from the position, orientation and form (Henzold, 2006). |
| Dimensional tolerance | The dimensional tolerance is a limit applied on dimensional (i.e. size) variations (Henzold, 2006). |
| Geometric tolerance | The geometric tolerance is a limit applied on form (i.e. geometry) of components (Henzold, 2006). |
| Tolerance incompatibility | Tolerance incompatibility refers to the connection of two materials with different levels of dimensional accuracy. An example of tolerance incompatibility includes the interface between metal curtain walls or partition walls with the concrete structural frame (American Concrete Institute, 2002). |
| Tolerance coordination | The main purpose of tolerance coordination is to ensure designs are constructible (Alshawi & Underwood, 1996; Rausch, Nahangi, Haas, & West, 2017). The tolerance coordination between designers, the construction team and the manufacturing supply chain is imperative (British Standards Institution, 1988a) to ensure tolerances of adjoining components are compatible (American Concrete Institute, 2014). |
| Sub-assembly | When there is a group of two or more components where each pair creates a joint or they are in a close proximity and, above all, they are connected to each other tolerance-wise, they make a sub-assembly. Being related tolerance-wise means that the accuracy of components affects each other's dimensional and geometric accuracy and the final function (adopted from Marguet & Mathieu, 2003). |
| Clearance | Clearance is defined as the space between two components (British Standards Institution, 2013). The provision of clearance helps designers accommodate variations in size, form and the angularity of individual components and accommodate building movement (Ballast, 2007). Also, clearance is sometimes needed between attached components, such as the space needed between the fireproofing protection and steelwork, or it is needed to allow working space during construction, for example the space needed for workers to tighten a bolt (Ballast, 2007). |
| Critical dimension | Dimensions on components and sub-assemblies should be labelled as critical or non-critical for function (Graves & Bisgaard, 1999). Critical dimensions are the ones that affects the functionality of the sub-assemblies more than other dimensions (Singh, Jain, & Jain, 2009). Hence, not all dimensions are important from the tolerance management perspective and it will not be economic and very time consuming if all dimensions are considered as critical (Graves & Bisgaard, 1999). The critical dimension must be within the tolerance specified by the designer to ensure the satisfactory functioning of the sub-assembly (Milberg, 2006; Singh et al., 2009). |
| Interface | The interface can be ascribed when there is clearance between two components that are in close proximity to each other (Ballast, 2007). |
| Joints | When two or more components are in a direct contact, they make a joint (British Standards Institution, 2013; Creveling, 1997). |

**Table 2-1 Continued**

| TERM | DEFINITION |
|---|---|
| Connection | Connection implies both interface and joint. |
| Fit | This term describes the satisfactoriness of a sub-assembly in relation to the identified requirements. The requirements in this context include limits of variations in clearances, and dimensional and geometric tolerances of components connected tolerance-wise (British Standards Institution, 1988b). Fit is achieved when requirements are addressed, components in sub-assembly function properly, and components are installed and assembled without any severe rework and modification (Bonshor & Eldridge, 1974; British Standards Institution, 1988b). |
| Lack of fit | The most immediate symptom of tolerance problem is lack of fit (Davison & Owens, 2012). It occurs when identified tolerance requirements are not satisfied. For example, the lack of fit may involve encroachment beyond the limit of required joint clearance (British Standards Institution, 1988b). |
| Tolerance problems | Tolerance problems include defects (e.g. lack of fit) incurred due to inherent or induced sources of dimensional and geometric variations. Tolerance problems may require rework to fix the problem or they may be accepted as they are. Tolerance problems can either be resolved by operatives or they may be communicated to foremen, main contractors, designers or other corresponding parties in order for them to find a solution (e.g. change the design, scrap, return to factory, major rework on site, use of filling materials, etc.) (adopted from Atkinson, 1998). |
| Tolerance risk | A tolerance risk is the exposure to the likelihood of an occurrence of tolerance problems which will adversely affect the project objectives (adopted from Al-Bahar & Crandall, 1990). |
| Tolerance requirement | A tolerance requirement is the required accuracy to mitigate tolerance risks and obtain desired functionality and aesthetic (adopted from Creveling, 1997). |
| Tolerance specification | It is about specifying tolerance values for components and sub-assemblies often based on reference documents (Milberg, 2006). |

## 2.3 Key Tolerance Concepts

Based on the literature that have explained the fundamental concept of tolerances in construction including British Standards (e.g. British Standards Institution, 1988a, 1990; British Standards Institution, 1998b, 2009a, 2009b, 2011) and books (e.g. Alexander, 2014; Davison & Owens, 2012), it appears that the key concepts relating to tolerances are (but not limited to): sources of dimensional and geometric variations, Characteristic Accuracy, classes of tolerances, and evaluation of combined deviations.

### *2.3.1 Sources of Dimensional and Geometric Variations*

Dimensional and geometric variations fall into two categories: induced variations and inherent variations (British Standards Institution, 1988a, 1990, 2013). Figure 2-2 presents a summary of the sources of dimensional and geometric variations. These sources are also explained below.

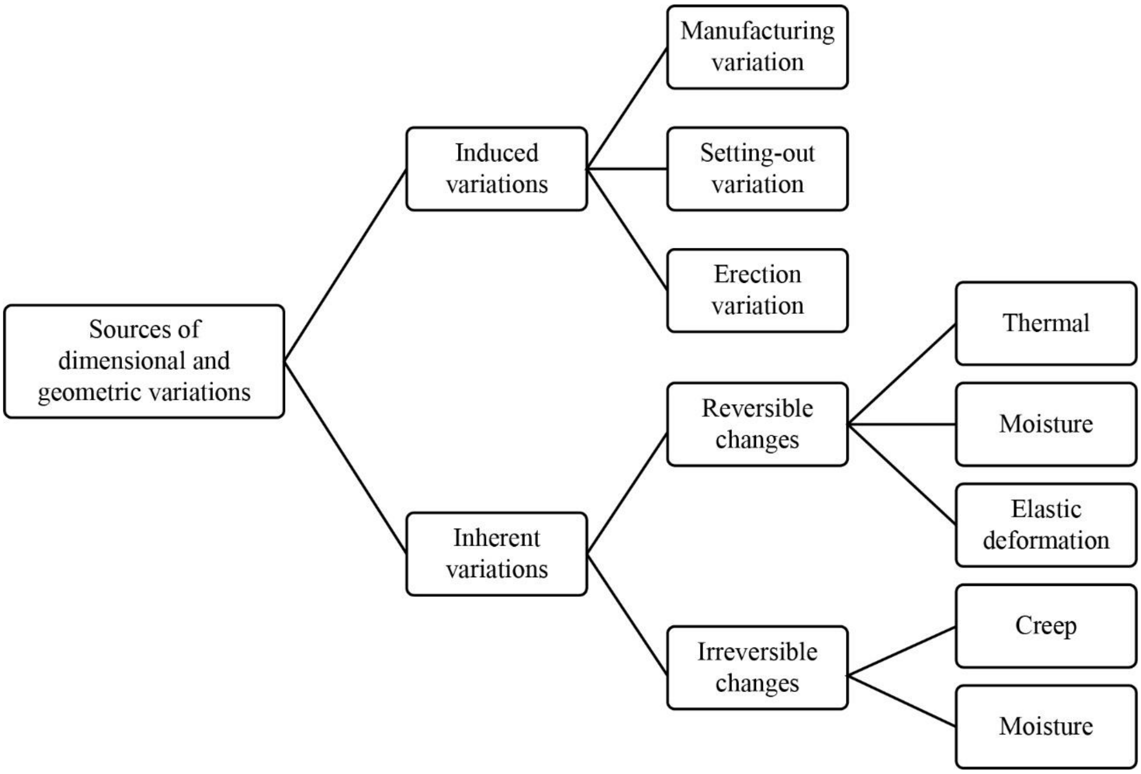



**Figure 2-2. Categorisation of the sources of dimensional and geometric variations (adopted from British Standards Institution, 1988a, 1990, 2013)**

### 2.3.1.1 Induced Variations

All processes of positioning, alignment and measurement are subject to variation due to the limitations of the measuring instruments used and human errors. This type of variation is termed induced and is categorised into three groups as shown in Table 2-2.

**Table 2-2. The types and definitions of induced variations (British Standards Institution, 1988a, 1998b)**

| TYPES OF INDUCED VARIATIONS | DESCRIPTION |
| --- | --- |
| Construction / manufacturing / fabrication | These variations are due to: (a) deviations in size or shape of components which arise during the manufacturing process, (b) variability of dimensions and shape in formwork, and (c) deflection of formwork and the settlement of its supports and props. |
| Erection deviation | These variations are due to: (a) the inability to locate and orient building components exactly on setting out marks, and (b) insufficient adjustability in fixing (e.g. clearance should be present in bolt holes to enable the bolts to pass through). |
| Setting-out deviation | These variations comprise of: (a) the human inability to measure and survey the site with absolute accuracy, which can then impact on the location of construction elements and components, and (b) the inaccuracy of measuring instruments, such as a total station. |

#### 2.3.1.2 Inherent variations

All materials exhibit dimensional and geometric changes over time as a result of physical or chemical causes. This type of variation is called an inherent variation (British Standards Institution, 1988a). It is more common among practitioners and in the literature to refer to this source of variation as building movement. Hence, hereafter, the term building movement is used. Building movement refers to the changes in the form and size of components after they are constructed (Alexander, 2014).

Movements normally occur over time when there is a change in loads being applied on the building or a change in materials (e.g. due to shrinkage). Movement may take place shortly after there is a variation in loadings or it may take place months or years after completion of the construction (American Society of Civil Engineers, 2011). The causes of inherent variations are deformation, drying shrinkage and moisture movement, foundation movement, and temperature and radiation (Alexander, 2014; British Standards Institution, 2009b). Further details about inherent variations are given in Appendix B.

#### 2.3.1.3 Summary of Sources of Variations

There are various sources of variations that can affect the dimensional and geometric accuracy of components and sub-assemblies. Such sources of variations are divided into two generic categories: induced variations and inherent variations. Induced variations stem from inaccuracy of measurement instruments and poor workmanship. They comprise of construction/manufacturing/fabrication deviations, erection deviations and setting-out deviation. Inherent variations, also called building movement, are caused by dimensional and geometric changes of materials over time.

### *2.3.2 Characteristic Accuracy*

The British Standards Institution (1990) presents the concept of Characteristic Accuracy. This concept is perceived as the underlying concept of tolerances in construction. This idea simply implies that a consistent pattern of dimensional and geometric variations occurs in any manufacturing or construction process, even when trained operatives, the correct tools, and the appropriate materials are used to achieve the specified dimensions and forms. The British Standards Institution (1990) states that it is not enough to just ask for more restrictive tolerances because variations are an inevitable characteristic of any manufacturing and construction processes. In order to provide a more detailed explanation of the concept of Characteristic Accuracy, the following three terms are briefly defined (British Standards Institution, 1990):

**Standard deviation (SD)**: This is the extent of the spread of the dimensional and geometric variations about the mean value.

**Normal distribution**: In any process, the dimensional and geometric variations are distributed about the mean value. This is known as a normal distribution. The normal distribution is bell-shaped in a way that a range of 1 SD about the mean value will include 68.27% of the survey (measurement) results, 2 SD will include 95.45% of survey results, and 3 SD will include 99.73% of survey results (Figure 2-3).

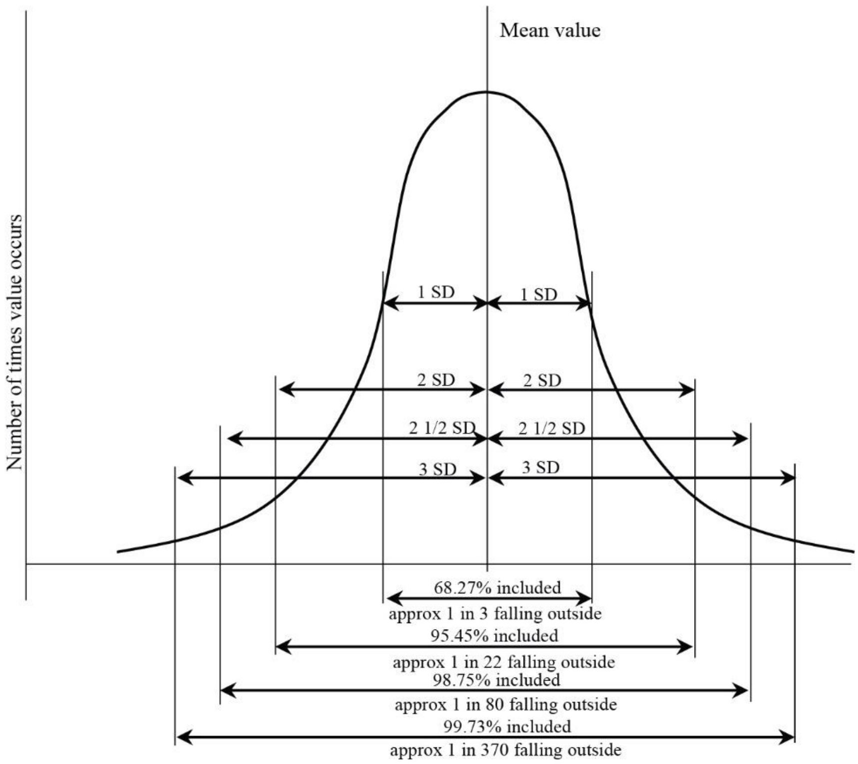



**Figure 2-3. Normal distribution of variations (British Standards Institution, 1990)**

Systematic deviation: The target size and form cannot be achieved in some manufacturing and construction processes. The difference between the target value and the mean value obtained from measurements is called systematic deviation, and is also called displacement of the mean. Apparently, the mean value is calculated by getting the average of the survey results. Figure 2-4 illustrates the concept of systematic deviation.

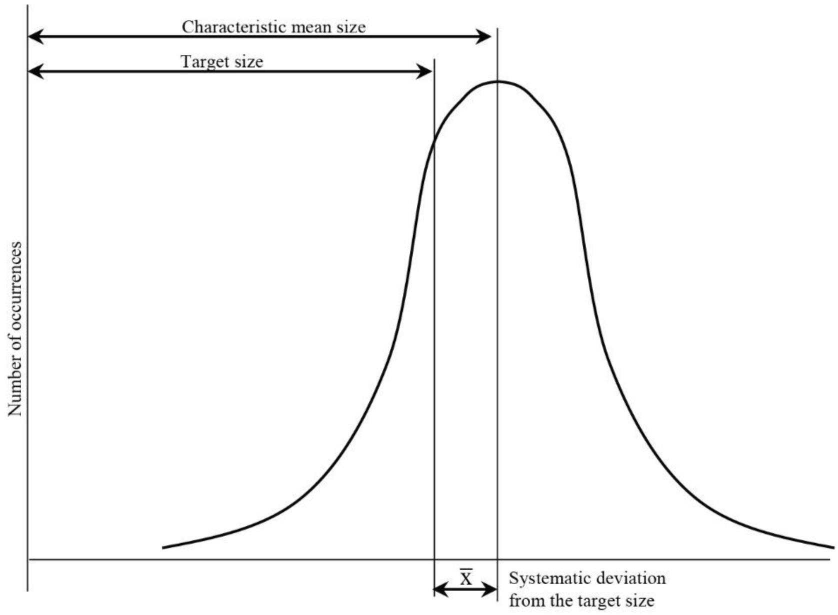



**Figure 2-4. Mean and the displacement from mean (British Standards Institution, 1990)**

Multipliers before the SD: Each of the multipliers before the SD implies a percentage of work that does not reach the specified permissible deviation (i.e. tolerance). The multipliers and the corresponding percentage of work, which probably does not fall within the specified tolerances, are given in Table 2-3. It should be noted that the permissible deviation is the largest accepted deviation (±) from the specified dimension. The permissible deviation is not expected to impair the function, constructability and aesthetics of the component. The standard deviation and systematic deviation are found by the measurement of a representative sample and taken to be characteristic of the whole.

**Table 2-3. List of multipliers and the associated percentage of work which does not reach specified standard (British Standards Institution, 1990)**

| MULTIPLIER | PERCENTAGE OF WORK WHICH PROBABLY DOES NOT REACH STANDARD SPECIFIED |
|---|---|
| 3 | 0.3 (or 1 in 370) |
| 2 | 4.5 (or 1 in 22) |
| 1 | 32.0 (or 1 in 3) |

Characteristic Accuracy is the accuracy of a component described in terms of SD and systematic deviations. To specify the Characteristic Accuracy, the appropriate multiplier for any permissible deviation should be obtained. The Characteristic Accuracy values for construction and Characteristic Accuracy values for manufactured components have been given in (British Standards Institution, 1990). To explain the concept of the Characteristic Accuracy further, an example is given in Appendix C.

#### 2.3.2.1 Summary of Characteristic Accuracy

Characteristic Accuracy is a foundational concept of tolerances in construction. It is defined in terms of the standard deviation or systematic deviation, or both, and it is found by the measurement of a representative sample. Characteristic Accuracy is perceived to represent the characteristic of the whole work. The values of the Characteristic Accuracy for manufactured components can be found in (British Standards Institution, 1990). The Characteristic Accuracy can be defined by obtaining an appropriate multiplier for any permissible deviation.

### *2.3.3 Classes of Tolerances*

It is important to recognise the required level of accuracy (i.e. class of tolerances) particularly at the tender stage of a construction project. This is because different classes of tolerances often have different cost implications (Davison & Owens, 2012). For instance, the final use of the floor and the importance of the flatness of the finished floor determine the required tolerance class for flatness (British Standards Institution, 2009b).

The categorisations of classes of tolerances are not well-defined in reference documents, and many different terms can be found. For example, (British Standards Institution, 2011) uses the terms essential, functional and special for the steelwork, (CONSTRUCT Concrete Structures Group, 2010) uses the terms class 1 and class 2 for the concrete structure, and (British Standards Institution, 2009a) uses the terms normal and special tolerances for the concrete structure. Having reviewed and interpreted those sources, a summary of the categorisation of classes of tolerances is given in Table 2-4.

**Table 2-4. Classes of tolerances in construction in different reference documents and their definitions**

| BRITISH STANDARDS INSTITUTION (2009A) | CONSTRUCT CONCRETE STRUCTURES GROUP (2010) | BRITISH STANDARDS INSTITUTION (2011) | DEFINITION (ADOPTED FROM BRITISH STANDARDS INSTITUTION, 2009A, 2011; CONSTRUCT CONCRETE STRUCTURES GROUP, 2010) |
|---|---|---|---|
| Normal | Class 1 | Essential | This class are necessary for all types of buildings and can be achieved by using typical materials and methods of working, e.g. conventional materials, a general standard level of workmanship and usual site conditions. This class of tolerances can be adopted from the reference documents. |
| Special | Class 2 | Functional | This class is more stringent than normal tolerances. It is used for certain needs of a given design and are applied to certain components or dimensions. An example of the need for having particular tolerances can be for boundaries or clearances. |
| Special | Class 2 | Special | This class is more stringent than normal tolerances and is applied to an entire building or structure. It may be necessary to use this class for particular appearance requirements, structural requirements (e.g. critical design criteria), or assembly requirements (e.g. interchangeability). |

#### 2.3.3.1 Summary of the Classes of Tolerances

The classes of tolerances represent different levels of accuracy in a project and they are expressed by different terms. According to the British Standards Institution (2011), such classes are divided into three categories: Essential, Functional and Special. The terms used by British Standards Institution (2011) seems more appropriate because they imply the corresponding definitions. Essential tolerances can be found in reference documents; Functional and Special tolerances are more stringent than normal tolerances. Functional tolerances are applied to curtain components whereas Special tolerances are applied to the entire structure or building.

### *2.3.4 Evaluation of Combined Deviations (Tolerance Analysis)*

The deviations of adjoining components are cumulative. The accumulated tolerance on the sub-assemblies must be less than or equal to the tolerance specified by the designer (Singh et al., 2009). The evaluation of the combined deviations is termed as the tolerance analysis (Henzold, 2006). In the tolerance analysis, the tolerances of components in a sub-assembly are all known and have been already specified. Therefore, the resulting tolerance of the sub-assembly is analysed (Chase & Greenwood, 1988). In Figure 2-5, the definition of the tolerance analysis is demonstrated.

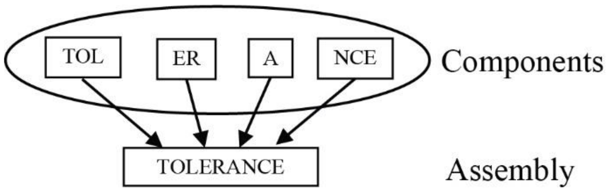



**Figure 3-5. Schematic representation of the tolerance analysis (adopted from Chase & Greenwood, 1988)**

The tolerance analysis for evaluating the combined deviation in construction is explained in (British Standards Institution, 1998b). The tolerance analysis provides a basis for the selection of the target sizes and the selection of connections that are capable of accommodating deviations adequately. Evaluating the combined deviations is difficult due to the different sources of variations that can affect the dimensional accuracy of components (British Standards Institution, 1998b). A failure to evaluate this can leave the trades with uncertainty about the total deviation of connections and sub-assemblies. This is because tolerances of adjoining components are cumulative (Rausch et al., 2017).

Both sources of variations (i.e. inherent and induced) can make components deviate from the nominal setting out dimensions (British Standards Institution, 1998b). The corresponding total variations due to the manufacturing/construction/fabrication, erection and setting-out deviations can be calculated using the square root of the sum of the squares of each the deviations (British Standards Institution, 1998b; Milberg, 2006; Singh et al., 2009). The Root Sum Squared method is as follows:

$$D_1 = \sqrt{(Manufacturing/Construction/Fabrication\ tolerance)^2 + (Erection\ Tolerance)^2 + (Setting\ Out\ Tolerance)^2}$$

Deviations due to inherent deviations ($D_2$) including deflection, temperature, moisture content etc. should be added arithmetically to the $D_1$ obtained above (British Standards Institution, 1998b). This approach is called the worst case method or the method of extremes. This approach assumes all the dimensions on the same side are at the extreme simultaneously (Singh et al., 2009). It must be recognised that the deflection tolerances should not be added to equation $D_1$ and must be summed only.

This is because all tolerances will not be cumulative due to their nature (British Standards Institution, 1998b). Hence, the Total Deviation (TD) can be found by (British Standards Institution, 1998b), as follows: Total Deviation (TD) = $D_1 + D_2$

The worst case method is applicable when 100 percent acceptance is required, whereas the root sum square method is applicable when a limited number of rejections of components and sub-assemblies are acceptable (Singh et al., 2009). The worst case method assumes the worst condition while the statistical variation analysis assumes the ideal scenario and underestimates variations (Singh et al., 2009). If the tolerance analysis is based on statistical assumptions, a probability of tolerance problems should be taken into account in the design (Singh et al., 2009). The probability of such problems should be decided based on the nature of the components, the type of construction and the types of connections used (British Standards Institution, 1988a).

#### 2.3.4.1 Summary of the Evaluation of Combined Deviations

There are two methods supported in the British Standards to calculate the combined deviations of components, namely: root sum square and worst-case analysis. If the Essential class of tolerances is used, the combined deviation due to induced variations is calculated using the square root of the sum of the squares of each deviation. The deviations due to inherent sources are then added arithmetically to the combined deviations obtained from the root sum square method.

### *2.3.5 Discussion*

Sources of dimensional and geometric variations, Characteristic Accuracy, classes of tolerances, and methods for tolerance analysis are the foremost (but not the only) fundamental concepts in tolerance management. These concepts are presented because understanding them is essential prior to reviewing the existing solutions for tolerance management. The reviewed literature is heavily based on the British Standards because tolerance-related concepts can be mainly found in such sources. Additional methods exist for tolerance analysis in the literature but those methods are not supported by the British Standards and other standard developing organisations and, hence their application in the industry cannot be envisaged, at least in the short time. Hence, only methods supported by the British Standards are considered in this research.

## 2.4 Tolerance Management in Construction

Tolerance management in construction is about utilising various tools and methods to: (a) reduce the variability derived from dimensional and geometric variations by identifying and mitigating tolerance risks (Shahtaheri et al., 2017), (b) increase transparency by visualising the interrelationship between components when subjected to deviations in an assembly (Milberg, 2006), (c) ensure designs are constructible (Alshawi & Underwood, 1996; Rausch et al., 2017), and (d) reduce lead times by avoiding tolerance problems and the associated modification process (Milberg, 2006). The ultimate aim of tolerance management is to minimise costs ("A checklist on tolerances," 1974), increase quality (Forsythe, 2006), and continually improve the management of tolerances (Milberg, 2006). These can only be achieved if more judicious decisions are made upstream in the process (Milberg, 2006).

In the construction industry, there is a need for a better solution to manage tolerances rather than ad hoc modification on site as stated by many authors (Anderson, 1965; Ballast, 2007; Bradford, 2017; Forsythe, 2006; Milberg, 2006; Shahtaheri et al., 2017), especially because the construction industry is currently in a difficult transitional state between being either craft-based or industrialised (Douglas & Ransom, 2013; Koskela, 1992). Some components that are produced off-site, such as glass and steel, have a high level of accuracy while it is difficult to reach as much precision in other components, such as in-situ concrete elements (Ballast, 2007; Milberg, 2006).

In this section, the proposed processes for tolerance management in the literature are presented.

### *2.4.1 Proposed Processes for Tolerance Management in Construction*

For this research, it is important to understand the processes and recommendations that exist in the literature on tolerance management. In Table 2-5, the most important guidelines found in the proposed processes and recommendations for tolerance management is given, and each of those guidelines are critically evaluated. In addition to the given sources, Milberg (2006) has proposed a process for tolerance management. However, this process has been excluded because the methods used in this process (e.g. tolerance mapping, vector loop and process capability) are outside the scope of this thesis as this research does not aim to generate or utilised any relatively complicated mathematical/engineering methods. A more detailed description of the existing process / recommendations on tolerance management is given in Appendix D.

**Table 2-5. The most important findings for tolerance management in the literature and their shortcomings**

| SOURCE | THE MOST IMPORTANT GUIDELINES | SHORTCOMINGS |
|---|---|---|
| "A checklist on tolerances" (1974) | Tolerances should be specified based on the stability and serviceability of the building, the capability of the construction team to achieve the required level of accuracy, and the sequence of assembly process.<br>A trade-off should be held between the cost of manufacturing and construction methods, and the cost of specifying more restrictive tolerances. | The recommendations given in this source show the depth of understanding of its authors about tolerance management at that time. More specifically, accounting for serviceability while ensuring stability, thinking about process capability, and considering the assembly process all seem promising solutions for tolerance management. However, this source does not provide any practical solution to achieve those objectives and it is limited to set up a vision for the industry. |
| CIRIA (1983) | Designers should choose appropriate details (e.g. appropriate connections) to avoid tolerance problems.<br>If more restrictive tolerances are needed than specified in the reference documents, appropriate actions should be taken.<br>There should be communication between the designers and the construction team to select realistic tolerance values.<br>The accuracy of the survey process should be specified. | This source only introduces a set of steps for tolerance management without providing any practical recommendations about how they should be conducted, by whom and when. More specifically, (a) it does not state what details in design can avoid conflicts between factory made components and site-made components, and (b) what tolerance information and should be incorporated in specifications and drawings and how this should be done.<br>This source only focuses at the design stage and disregards tolerance management in other stages of a project such as construction. |
| British Standards Institution (1988a) | Tolerances should be specified at least for critical dimensions and positions. | No process has been proposed in this source except a recommendation for specifying tolerances for critical dimensions. |
| Vorlíček and Holický (1989) | The identified tolerance requirements must ensure compliance with the functional requirements (i.e. stability and serviceability).<br>In effective tolerance management, the constraints of manufacturing and construction, the cost of the production process, and the functional requirements should be taken into account simultaneously. | No process has been proposed in this source except a set of conclusions that should be considered in tolerance management.<br>The focus of this source is only on structural design. |

**Table 2-5 Continued**

| SOURCE | THE MOST IMPORTANT GUIDELINES | SHORTCOMINGS |
|---|---|---|
| British Standards Institution (1990) | In effective tolerance management, the areas with a high risk of tolerance problems (i.e. areas where (a) there are critical dimensions, and (b) tolerance problems may occur) should be identified and tolerance requirements should be communicated with project members. | In this source, critical dimensions are not defined, and areas in which tolerance problems are likely are not specified.<br>One of the recommendation is about choosing achievable tolerances. Nevertheless, the document does not state how achievable and realistic tolerance values can be found and assigned.<br>No process has been proposed in this source except a set of recommendations. |
| Precast/Prestressed Concrete Institute (2004) | The responsibility of the tolerance specification and control should be assigned to the project members, tolerance management starts from early design, and restrictive tolerances should be avoided. | No process per se for tolerance management has been proposed in this source except a set of recommendations scattered throughout the handbook. |
| Ballast (2007) | Designers are responsible for tolerance management; *in situ* components should have tolerances as stringent as possible;<br>Communication of tolerance information should include the permitted deviations, the reference documents used, and the method to verify the compliance of the achieved accuracy;<br>Tolerance problems should be resolved through general agreement, especially when tolerance values for a component could have not been identified in reference documents. | No process has been proposed in this source except a set of recommendations that should be used in tolerance management. |
| American Concrete Institute (2014) | It is useful to arrange tolerance coordination meetings.<br>In effective tolerance management: (a) tolerance information (i.e. tolerance requirements of constructed components, tolerance risks, and required clearance) should be collected from appropriate reference documents, designers, construction team and manufacturers, (b) compatibility of the specified tolerances of adjoining components should be evaluated, and (c) appropriate mitigation strategies (e.g. the use of filler materials, the use of adjustable connections) for tolerance risks should be collectively found. | The process proposed in this source is probably the most comprehensive process for tolerance management that exists in the literature. However, it is limited to the connection between concrete elements and other components, and it is applicable only in the traditional procurement system.<br>This source does not provide any specific, practical recommendations about how to follow the proposed steps. For example, what tolerance requirements are, how those requirements should be captured, how tolerance risks should be identified, what measurement protocol is, and how it should be established.<br>It does not provide any detailed description on how tolerance analysis should be provided.<br>The proposed process focuses on the design stage only. |

#### 2.4.1.1 Summary of Proposed Processes / Recommendations for Tolerance Management in Construction and Discussion

A summary of recommendations / steps about how to improve tolerance management in construction is given in Table 6. Based on reviewing the literature around tolerance management in construction, it appears that only (CIRIA, 1983) and (American Concrete Institute, 2014) propose a process with a set of steps for tolerance management. The remaining sources are limited to some recommendations. Those processes for tolerance management comprise a set of steps in which various activities should be carried out. Each step is focused on a specific aspect of tolerance management.

The two proposed processes and all recommendations are mainly focused on the design stage and disregard the other stages of a project. Continuous improvement is an important aspect of tolerance management as it is essential for avoiding tolerance problems (i.e. defects) (Johnsson & Meiling, 2009; Meiling et al., 2014) but it is missing in those two processes. Neither of the proposed processes specify precisely how the recommendations and steps should be carried out and by whom exactly, and they are limited to generic recommendations. Each source provides useful recommendations for tolerance management but neither of them encompasses all those recommendations comprehensively. In other words, a holistic process for tolerance management, starting from early project stages to completion, with in-depth and clear recommendations (e.g. responsible for the provision of information) while considering continuous improvement is still missing in the literature.

**Table 2-6. Recommendations/steps given in the literature related to tolerance management in construction and corresponding sources**

| RECOMMENDATIONS / STEPS | SOURCES |
|---|---|
| Start of tolerance management from early stages of a project | Precast/Prestressed Concrete Institute (2004) |
| Appointment of project members for tolerance management | Precast/Prestressed Concrete Institute (2004) |
| Appointment the engineer or architect for tolerance coordination | American Concrete Institute (2014) |
| Appropriate design of connections | CIRIA (1983)<br>British Standards Institution (1990)<br>Precast/Prestressed Concrete Institute (2004)<br>Ballast (2007)<br>American Concrete Institute (2014) |
| Collection of tolerance information from reference documents, manufacturers, designers, contractors and users | American Concrete Institute (2014) |
| Determination of class of tolerances to ensure stability and serviceability | "A checklist on tolerances" (1974)<br>CIRIA (1983) |
| Calculation of building movement | CIRIA (1983) |
| Communication of tolerance information | CIRIA (1983)<br>British Standards Institution (1990)<br>Ballast (2007)<br>American Concrete Institute (2014) |
| Identification of tolerance requirements | Vorlíček and Holický (1989)<br>American Concrete Institute (2014) |
| Identification of tolerance risks | British Standards Institution (1990)<br>American Concrete Institute (2014) |
| Evaluation of combined deviations | British Standards Institution (1990)<br>American Concrete Institute (2014) |
| Determination of the sequence of assembly process | "A checklist on tolerances" (1974) |
| Generation of solutions to mitigate tolerance risks | British Standards Institution (1990)<br>American Concrete Institute (2014) |
| Specification of tolerances based on process capability | "A checklist on tolerances" (1974)<br>British Standards Institution (1988a)<br>British Standards Institution (1990)<br>Precast/Prestressed Concrete Institute (2004) |
| Specification of limits for sources of variations | Ballast (2007)<br>American Concrete Institute (2014) |
| Meetings for tolerance management | Ballast (2007)<br>American Concrete Institute (2014) |
| Selection of appropriate construction methods | Vorlíček and Holický (1989) |
| Measurement of deviations | CIRIA (1983)<br>Vorlíček and Holický (1989) |
| Communication of the measurement protocol | Precast/Prestressed Concrete Institute (2004)<br>Ballast (2007) |
| Control of compatibility of adjoining components | American Concrete Institute (2014) |

## 2.5 Tolerance Management in Manufacturing

Given that the characteristics of tolerance problems in the construction and manufacturing industries can be considered similar (Milberg, 2006), some manufacturing strategies and methods can be potentially applied to construction (Milberg, 2006; Rausch et al., 2017). Moreover, there are numerous contributions to different aspects of tolerances of mechanical assemblies with different depth and breadth over the decades. This shows the importance and significant developments of the topic in manufacturing (Hong & Chang, 2002; Singh et al., 2009). All in all, it seems essential to review how tolerances are managed in manufacturing and if applicable, adopt appropriate strategies and methods to construction.

The term tolerance management is not commonly used in manufacturing, except in a few publications (e.g. Chase & Parkinson, 1991; Graves & Bisgaard, 1999). Instead, terms like dimensional management (e.g. Craig, 1996; Curtis, 2002) and variation management (e.g. Giordano, Mathieu, & Villeneuve, 2012; Thornton, 2004) tend to be used. Despite the acknowledged importance of tolerances in manufacturing and advances that have been made in this field, tolerance problems, even in manufacturing, are still often identified at the end of the assembly process when parts are put next to each other and sub-assemblies are created (Costadoat, Mathieu, Falgarone, & Fricero, 2012; Marguet & Mathieu, 1998).

There are many proposed methods in the literature for tolerance management in manufacturing. Most of them revolve around 1D, 2D or 3D tolerance analysis, Geometric Dimensioning and Tolerancing (GD&T), and the use of commercial software programmes for tolerance modelling, tolerance analysis, and tolerance allocation (Ghali, Tlija, Aifaoui, & Pairel, 2017; Islam, 2007). In other words, most of the research in tolerance management in manufacturing is about relatively complicated methods for tolerance analysis and allocation or the role of technology, rather than proposing a process.

GD&T is mainly a mechanical engineering tool which is expected to be applicable in the construction industry (Milberg, 2006). However, this tool includes several rules that make its use in construction tedious (Rausch et al., 2017). Hence, an in-depth exploration of this tool is out of the scope of this research. Regarding the tolerance analysis, apart from the time constraints and the management-orientation of this thesis, the reasons that tolerance analysis is out of the scope of this research is that the author believes that an extensive application of these methods in construction cannot be envisaged, at least in the short term. This is because, for example, there is lack of data on process capability to apply six sigma (Milberg & Tommelein, 2004), the Monte Carlo simulation requires intensive computational process (Singh et al., 2009), kinematic based dimensional variation analysis is not able to account for building movement (Rausch et al., 2019), and above all, standard-developing organisations currently do not support them. Therefore, the author sought for processes that: (a) are mainly concerned with the managerial aspects of tolerances rather than those that are focused on specific technical aspects of tolerance management (e.g. tolerance analysis, computer simulation), and (b) seem applicable for construction.

### *2.5.1 Proposed Processes for Tolerance Management in Manufacturing*

One of the authors who proposed a process for tolerance management is Mark Craig, a former CEO of General Motors. Craig (1996) introduces a method which aims to "create a design and process that absorbs as much variation as possible without affecting the function of the product" (p. 12).

This method has five steps for tolerance management as follows:

- **Step one (clearly define tolerance requirements)**: This step is about documenting the target variations, and the functional requirements of products in specifications;
- **Step two (ensure that the tolerance information is documented correctly)**: This step aims to ensure that the collected information in step one is understood by all the project members. This step is of a prime importance to create a consistent understanding of the functional requirements and specified tolerances of the products;
- **Step three (a measurement plan that validates tolerance requirements)**: A measurement plan as part of the tolerance specifications is required. This is because the specified permitted deviations for products and sub-assemblies need to be measured during manufacturing and assembly;
- **Step four (analysis of measurement results)**: After implementing the measurement plan, it should be investigated whether the tolerance requirements have been achieved;

- **Step five (analysis of tolerance problems)**: If the final deviations do not fall within the specified limits, the actual variations should be analysed. This is to determine if exceeding deviations than the specified tolerances adversely affect the functional requirements, and if yes, to reduce adversarial impacts of such exceeding deviations.

Mantripragada and Whitney (1998) discuss tolerance management for the aircraft industry. Tolerance management in this context, on the one hand, deals with accepting the largest dimensional and geometric variations, that is lower cost, but, on the other hand, deals with ensuring functional requirements are satisfied, that is, the desired level of quality is attained. According to Mantripragada and Whitney (1998), tolerance management in the aircraft industry has three main pillars as follows:

- **Specification**: tolerances that guarantee the satisfaction of functional requirements should be specified;
- **Analysis**: the consequences of specified tolerances on the functional requirements should be analysed;
- **Synthesis**: It should be investigated whether tolerances can be optimised (e.g. more relaxed tolerances may be specified while functional requirements are still satisfied).

Marguet and Mathieu (1998) argue that tolerance management should be both a top-down and bottom-up approach. The top down approach in tolerance management requires users to shift their focus from being product centric (i.e. focusing only on tolerances of products) to being focused on sub-assemblies and connections (Marguet & Mathieu, 1998), although most of the literature found in the manufacturing are focused on an individual product and not on assemblies (Graves & Bisgaard, 1999; Krogstie, Walter, Wartzack, & Martinsen, 2015).

Such a process for tolerance management in the aircraft industry is as follows (Marguet & Mathieu, 1998):

- The design starts with a general description of the tolerance requirements in an assembly based on the client/user needs;
- Connections must be explicitly identified because the identification of connections is a prerequisite to plan the assembly process and tolerance analysis;

- The design should be developed by deploying a bottom-up approach in which tolerances of components are adopted from the reference documents;
- Realistic tolerances, based on both the client/user requirements and expected tolerances in reference documents are selected for components and sub-assemblies;
- The requirements are systematically explored in details, verified, formalised and then flowed down to sub-assemblies and individual components.

Another important factor in tolerance management in the aircraft industry is that designing products that are easy to produce and assemble is only possible if all project participants (e.g. designer, manufacturer, etc.) are working together to create an integrated team. The first element that the team should account for is how the products are supposed to work and be used (Mantripragada & Whitney, 1998; Marguet & Mathieu, 2003; Thornton, 2004).

Costadoat et al. (2012) suggest that the tolerance management in general should start from the early design stage. The main idea is that the tolerance specification of individual components should evolve in parallel with the design while bearing in mind the assemblability and other tolerance requirements. This is to ensure that the specified tolerances are appropriate with the developed design at any time. In this approach, tolerances are not only taken into account at the end of the design stage but also throughout the design stage (Costadoat et al., 2012). Similarly, in a method for tolerance management, termed Integrated Tolerancing Process (ITP), the purpose is to ensure functional requirements are satisfied by selecting achievable tolerances. ITP starts from conceptual design and continuously proceeds to the final stage of design. The conceptual design first includes a high level description of requirements related to tolerances and continues to a high level description of the solutions (Dantan, Anwer, & Mathieu, 2003). If tolerance risks are recognised early, the time and cost needed to develop the product will significantly reduce and the quality of the final product will improve (Marguet & Mathieu, 1998).

Eventually, specifications should be converted to a simple language and a standard format. In this process, given that the specification of tolerances is gradually developed throughout the design stage, tolerance requirements and risks are identified by the involved project participants. Hence, this makes the work of the designer much easier (Costadoat et al., 2012).

### 2.5.2 Summary and Discussion

Tolerance management in manufacturing is not considered as a linear process in which tolerances are specified, components are manufactured/constructed and then fabricated/erected. Instead, tolerance management is an on-going and iterative process. In such a process, specification, production and inspection are equal to make a hypothesis (e.g. tolerance values, assembly sequence, etc.), carry out an experiment (i.e. assembly process), and test the hypothesis to investigate whether the required accuracy has been obtained. A summary of the steps in tolerance management in manufacturing is given in Table 2-7.

**Table 2-7. Recommendations / steps given in the literature related to tolerance management in manufacturing and corresponding authors**

| RECOMMENDATIONSSTEPS | AUTHORS |
| --- | --- |
| Connections should be identified | Marguet and Mathieu (1998) |
| General tolerance requirements should be captured early design (e.g. finding tolerance values from reference documents) | Craig (1996)<br>Marguet and Mathieu (1998) |
| Realistic tolerance values should be specified based on reference documents and the Client/user expectations | Marguet and Mathieu (1998) |
| Tolerance analysis and synthesis should be performed | Mantripragada and Whitney (1998) |
| The specified tolerances and functional requirements should be documented in specifications (i.e. communication of tolerance information) | Craig (1996)<br>Mantripragada and Whitney (1998) |
| A measurement plan should be created | Craig (1996) |
| The measurement results should be analysed | Craig (1996) |
| Tolerance problems should be analysed to determine if exceeding deviations adversely affect the functional requirements | Craig (1996) |
| The focus of tolerance management should be on whether functional requirements are satisfied | Mantripragada and Whitney (1998) |
| Tolerance management should be a top-down approach in which tolerances in sub-assemblies are taken into account | Marguet and Mathieu (1998) |
| Tolerance management should be a bottom-up approach which tolerances of components are adopted from the reference documents | Marguet and Mathieu (1998) |
| All project participants should create an integrated team to perform tolerance management | Marguet and Mathieu (1998)<br>Dantan, Anwer, and Mathieu (2003)<br>Thornton (2004) |
| Tolerances should be taken into account throughout the design | Costadoat, Mathieu, Falgarone, and Fricero (2012) |
| At the conceptual design, a high level description of tolerance requirements should be taken into account | Dantan et al. (2003) |
| Tolerance risks should be identified at early stages of the project | Marguet and Mathieu (1998) |
| Tolerance requirements and risks should be translated into a simple language | Costadoat et al. (2012) |

Some recommendations between the literature related to tolerance management in manufacturing and construction are found to be similar (e.g. performing tolerance analysis, creating measurement plan). However, there are still lessons to be learned from manufacturing that should be into taken account when developing a solution for tolerance management in construction. Those lessons are the essence for identifying connections, specifying realistic tolerance values by accounting for the client/ user expectations, analysing measurement plans, analysing tolerance problems, considering functional requirements in tolerance management, applying the top-down and bottom-up approaches in tolerance management, the need for an integrated team for tolerance management, describing a high level tolerance requirements at the concept design, translating tolerance requirements and risks into an understandable language for all the project participants. Like construction, the challenge with the recommendations given in the literature in manufacturing is that the literature is limited to generic recommendations and practical guidelines are hardly given.

## 2.6 Root Causes of Tolerance Problems in Construction

It is crucial to find the root causes of problems occurring in construction, otherwise the problems are being ignored or marginalised (Douglas & Ransom, 2013). Root cause can be defined as the basic reason at the highest level of a system that leads to a problem (Andersen & Fagerhaug, 2006). Liker (2004) states that solving a problem by finding suitable cures and designating workable mitigation strategies first requires identifying the root cause through digging deeper, rather than only referring to an immediate cause. More specifically, designing a solution to move from being reactive to proactive in managing tolerances, requires the identification and elimination of root causes of tolerance problems (Johnsson & Meiling, 2009; Meiling et al., 2014).

Berg and Holicky (1989) state that ambiguous communication of tolerance requirements, insufficient tolerance information in specifications, and negligence of tolerances during the tender process are the root causes of tolerance problems. Seymour et al. (1997) add four more causes for tolerance problems: (a) poor workmanship, (b) poor tolerance compliance control, (c) an over-reliance on unrealistic standards, and (e) conventional contractual and procurement systems impeding collective decision making when choosing realistic tolerance values. Milberg (2006) argues that (a) incomplete or missing tolerance information in specifications, which results in multiple interpretations of tolerance requirements by contractors and inspectors, (b) specification of unrealistic tolerance values, and (c) poor workmanship, are the major root causes of tolerance problems.

Other root causes of tolerance problems found in the literature include: (a) the lack of terminology to communicate tolerance information (i.e. characteristic of tolerances and tolerance values) (Brookes, 2005), (b) the lack of tolerance coordination between design disciplines and construction trades involved in assemblies (American Concrete Institute, 2014; Demian & Fruchter, 2006), and (c) the lack of the provision of appropriate connections to absorb deviations (Alexander, 2014; Williams, 2007).

Jingmond and Ågren (2015) contend that tolerance problems are either due to exogenous factors related to manufacturing tolerances or endogenous factors related to construction tolerances. They adopt an approach based on the use of cognitive mapping and the notion of process causality in order to identify causes of defects in construction. They believe that causes of defects associated with tolerances are: the lack of standard tolerances for all components, materials and connections, inaccuracy of the execution of work on site (e.g. when erecting prefabricated walls), unforeseen behaviour of materials, and the inaccuracy of equipment used for installation and measurement. Regarding the latter root cause, measuring devices range from moderately accurate (e.g. measuring tapes) to extremely accurate (e.g. automated electronic devices) (Ballast, 2007). The inaccuracy of measurement devices may be considerable relative to allowed deviations of structures and component that are connected to the structures (British Standards Institution, 1990). The utilisation of conventional instruments has remained laborious and time-consuming because they heavily rely on sampling techniques. The process of sampling is labour intensive which makes the results prone to the risk of being inaccurate (Phares, Washer, Rolander, Graybeal, & Moore, 2004). The challenge with the application of the recently developed measurement instruments (e.g. laser scanner) is due to a lack of adequate research on their level of accuracy (Bosché & Guenet, 2014).

The construction industry is currently in a transitional state. It is neither completely craft-based, nor is it industrialised Koskela (2000). Hence, it is essential to refer to standards and to understand what normal tolerances are (Ballast, 2007). However, there are still many construction tolerances that do not exist as industry standards (Ballast, 2007; Jingmond & Ågren, 2015), and the existing standard tolerances may be either unreasonably tight or loose (Ballast, 2007). Holbek and Anderson (1977) state that although tolerances in the construction industry have been developed for materials, such as steel and concrete, there is little input on the issue of conflicting tolerances at the interfaces between different materials and components. Many years later, the industry still struggles with the same challenge and the subject of interfacing between components is yet to be resolved (Bradford, 2017).

The verification of the compliance of tolerance requirements on site is performed according to the reference documents listed in specifications provided by the designers (Frank, 2012). Shammas-Toma, Seymour, and Clark (1996) argue that this is an ineffective quality control process and should be replaced by Quality Control documents in which achievable tolerance values based on project conditions can be found.

All building components are subject to variation in their size, form, orientation and position which cannot be precisely determined at the design stage (Vorlíček & Holický, 1989). Given the changes in the properties of materials used in the industry, the buildings are becoming structurally more flexible, more vulnerable to temperature variation, and less able to absorb and distribute movements (Alexander, 2014; Alexander & Lawson, 1981; Lawson, Ogden, & Goodier, 2014). The building process itself adds more inevitable geometric variations to components because the amount of loads being applied to the building structure gradually increases during the construction process and this leads to more building movement (Robertson & Naka, 1980). Variations are accumulated through components and assemblies that can result in the lack of fit or malfunction of assemblies (British Standards Institution, 1990). Designers have to not only account for the impact of every source of variation individually, but also the impact of variations when combined on dimensional and geometric characteristics of components and assemblies (Milberg & Tommelein, 2005). However, firstly, the industry lacks an accurate and validated guidance to anticipate the exact movements (Alexander, 2014); secondly, designers sometimes ignore the impact of combined deviations (Milberg & Tommelein, 2005; Rausch et al., 2017).

### *2.6.1 Summary of the Root Causes of Tolerance Problems*

Table 2-8 lists the references discussing the root causes of tolerance problems and their corresponding letter. Table 2-9 summarises the identified root causes of tolerance problems in the literature and shows the authors discussing each root cause.

**Table 2-8. Authors discussing root causes of tolerance problems and the corresponding letters**

| REFERENCES | CORRESPONDING LETTERS |
|---|---|
| (Holbek & Anderson, 1977) | A |
| (Berg & Holicky, 1989) | B |
| (British Standards Institution, 1990) | C |
| (Alshawi & Underwood, 1996) | D |
| ((Shammas-Toma, Seymour, & Clark, 1996) | E |
| (Feld & Carper, 1997) | F |
| (Seymour, Shammas-Toma, & Clark, 1997) | G |
| (Milberg & Tommelein, 2004) | H |
| (Phares, Washer, Rolander, Graybeal, & Moore, 2004) | I |
| (Brookes, 2005) | J |
| (Milberg & Tommelein, 2005) | K |
| (Milberg, 2006) | L |
| (Ballast, 2007) | M |
| (Williams, 2007) | N |
| (Alexander, 2014) | O |
| (Jingmond & Ågren, 2015) | P |
| (American Concrete Institute, 2014) | Q |
| (Rausch et al., 2017) | R |
| (Bradford, 2017) | S |

**Table 2-9. Root causes of tolerance problems identified in the literature and the list of authors discussing those root causes**

| IDENTIFIED ROOT CAUSE OF TOLERANCE PROBLEMS | AUTHORS DISCUSSING THE IDENTIFIED ROOT CAUSES |
|---|---|
| Inefficacious reference documents | A, B, G, L, M, O, P, Q, S |
| Poor communication of tolerance information | B, D, L, P |
| Negligence of tolerances during the tender process | B |
| Inaccuracy of measurement devices | C, H |
| Poor workmanship | F, L, P |
| Conventional contractual and procurement systems impeding collective decision making to choose realistic tolerance values | F |
| Design of inappropriate connections | E, N, O |
| The lack of terminology to communicate tolerance information | J |
| The lack of tolerance coordination during the project | L, P, Q |
| The lack of training | L |
| The lack of an accurate guidance to anticipate the exact building movements | O |
| Poor tolerance compliance control | F, P, S |
| Insufficient tolerance information in specifications | L |
| Specification of unrealistic tolerance values | L |
| Unforeseen behavior of materials (i.e. unforeseen movement) | P |
| Ineffective Quality Control documents | E |
| Ignorance of combined deviations | K, R |

### 2.6.2 Discussion

In this section, the identified root causes of tolerance management in the literature, existing/potential solutions to resolve them, and shortcomings of the existing literature on root causes of tolerance problems are discussed. 'Inefficacious reference documents' appears to be the most cited root cause of tolerance problems. Milberg (2006) and Milberg and Tommelein (2003a) propose a method whereby the reliance on reference documents can be reduced but it requires difficult calculations and it is time consuming to use. 'Poor communication of tolerance information' is a root cause for tolerance problems. Solutions to tackle this root cause are presented in Section 2.8. Regarding the 'negligence of tolerances during the tender process', no specific solution in the literature could be found to tackle this root cause. Different sources of variations are discussed in Section 2.3.1 but no literature could be found about how to make designers aware about such sources of variations. 'The lack of terminology to communicate tolerance information' is another root cause for tolerance problems. Terms used in manufacturing can be potentially adopted for construction in order to resolve this root cause. Further details can be found in Section 2.12. Regarding 'Poor tolerance compliance control', American Concrete Institute (2014) suggests to create a measurement protocol to improve tolerance compliance control on site but does not propose any specific solution about how to prepare such protocol, who should prepare it and when, and how it should be communicated. This is discussed in more detail in Section 2.8. The remaining root cause found in the literature i.e. poor workmanship, conventional contractual systems, the lack of a method for tolerance analysis, undeveloped technology, the lack of training, inaccuracy of manufacturing process, inaccuracy of measurement devices, and the lack of an accurate guidance to anticipate the exact building are not intended to be investigated in this research. The reason is that they are out of the scope of this thesis which is more focused on managerial aspect of tolerance management and/ or they should be treated as an independent research.

Based on the literature review to find root causes of tolerance problems, it appears that prior studies concerning the root causes of tolerance problems are restricted due to one or more of the following reasons: (a) they mainly represent the viewpoints of the industry practitioners and often are not based on empirical data (Forsythe, 2006), (b) they do not investigate the root causes of tolerance problems in a broad construction setting, from project management to engineering and from design to construction, and (c) they mainly focus on one aspect of tolerance problems (e.g. the measurement of deviations, tolerance analysis, etc.). As such, it is possible to state that the extant research tends to discuss root causes in a superficial manner by placing the responsibility with designers, operatives, and quality systems. These restrictions have made the root causes of tolerance problems obscure. Given these shortcomings, a thorough root cause analysis for tolerance problems is needed prior to any attempt to develop a solution for tolerance management. The root cause analysis should be based on empirical data, should investigate root causes from early stages of a project to completion, and should analyse root causes of tolerance problems from various aspects.

## 2.7 Construction Project Management

This section aims to explore concepts and methods from construction management that can be potentially used for developing a solution for tolerance management.

### *2.7.1 Continuous Improvement (Kaizen)*

Reducing tolerance problems and removing their causes is the essence of continuous improvements and learning from experience (Johnsson & Meiling, 2009; Meiling et al., 2014). Deming (2000) states that Continuous Improvement (CI) is about improving the system of production constantly. More specifically, CI is "an organisation-wide process of focused and sustained incremental" improvements (Bessant & Francis, 1999, p. 1106). In simple terms, CI is an approach by which: (a) small incremental improvement steps are taken to improve performance (Slack, Chambers, & Johnston, 2010) and (b) waste in all processes of an organisation are identified, reduced and eliminated (Bessant, Caffyn, & Gallagher, 2001; Bhuiyan & Baghel, 2005). CI is at the heart of Lean (Womack, Jones, & Roos, 1990). In the 4P model of the Toyota Production System, systematic problem solving is at the top of the pyramid and it should enable continuous improvement and the development of a learning organisation (Liker, 2004). CI is widely known as 'Kaizen', which is a compound word in Japanese (Imai, 2012). This word comprises two concepts: Kai (change) and Zen (improve) (Sanchez & Blanco, 2014). This word implies "improvement that involves everyone, both managers and workers, and entails relatively little expense" (Imai, 2012, p. 21).

The first step in establishing a Kaizen process is to create the plan-do-check-act (PDCA) cycle. The PDCA cycle is a means to ensure both maintaining and improving standards. In simple words, PDCA means one should never be satisfied with the status quo (Imai, 2012). In this cycle (Gitlow & Gitlow, 1987; Imai, 2012; Slack et al., 2010):

- '**Plan**' is about: (a) establishing a target for improvement, (b) collecting data based on that which a plan can be developed to achieve target requirements, and then (c) developing action plans to obtain that target;
- '**Do**' is about taking the necessary actions to implement the plan;
- '**Check**' is about collecting data to investigate whether the implementation is on track and the planned improvements are achieved;
- '**Act**' is about standardising the new procedures. This is to ensure that occurred problems do not reoccur and goals for the new improvements are also established.

One of the most important means of Kaizen is standardisation (Ballé & Ballé, 2009). The standardisation in processes is not only an approach to ensure quality but it also prevents the recurrence of defects (Imai, 2012). The best way to do a particular job is called standard (Hales & Gooch, 2011; Imai, 2012). There are two types of standards: managerial standards and operational standards. The former is related to the management of employees for administrative purposes (e.g. job descriptions). The latter is related to how employees will do a job while bearing in mind quality, cost and delivery (Imai, 2012). Some of the key features of standards are as follow (Imai, 2012):

- Standards reflect the experience of employees about know-how. Standards can help employees to maintain a certain way of doing jobs and make sure all the workers follow the same procedures that are the most efficient and cost-effective way of doing specific jobs;
- Standards preserve the implicit knowledge of employees about know-how. Standardising such knowledge leads to maintaining the knowledge inside the organisation regardless of whether individuals stay;

A tool that is known as CI tool and can help establish the PDCA cycle in practice is described next, namely A3 reports.

#### 2.7.1.1 A Continuous Improvement Tool: A3 Reports

An A3 report is a system for implementing Kaizen and it is considered as a general management approach. It is a one-page document that records the main results found from the PDCA cycle (Sobek II & Smalley, 2011). A3 reports have become a standard management approach for summarising problem solving exercises (Lean Enterprise Institute, 2003). The reason behind the name of this system is that those reports are typically fitted on one side of an A3-sized sheet of paper. Note that the completion of an A3 report cannot be adequate without having an appropriate process in place. In fact, the A3 reporting process should be considered as a way of thinking (Flinchbaugh, 2012; Sobek II & Smalley, 2011).

The overall flow of the report is about the PDCA cycle. The left hand side of the report is allocated to the Plan part of PDCA and the right hand side is devoted to the Do, Check and Act part of PDCA cycle (Imai, 2012). Sobek II and Smalley (2011) propose that an A3 report should include seven sections (Figure 2-6). Those sections are described separately below (Sobek II & Smalley, 2011):

- **Background**: Any background information about the problem should be documented. It is suggested that the background information is communicated visually;
- **Current condition and problem statement**: The objective of this section is to explain the current condition in a simple language;
- **Goal statement**: The goal statement should be about how it can be ensured that the project is successful when the implementation ends;
- **Root cause analysis**: The problem-solvers should continue the investigation of the current condition until they can uncover the main root cases of the identified problem. The findings from the root cause analysis should be preferably visually summarised;
- **Countermeasures**: The countermeasure section of the A3 report should be set out like an action list of how to resolve the problem;
- **Check/confirmation of effect**: An elements of the thinking behind the A3 report should be presented in the check/confirmation section of the report: whether the problem-solver has used a basis or standard to confirm whether the planned actions have had the intended effect;
- **Follow up actions**: This section in light of the learning gained consists of: (a) what remains to be done in the future in order to expand the improvement, and (b) what further actions should be taken to ensure the improvements gained from the countermeasures are sustained.

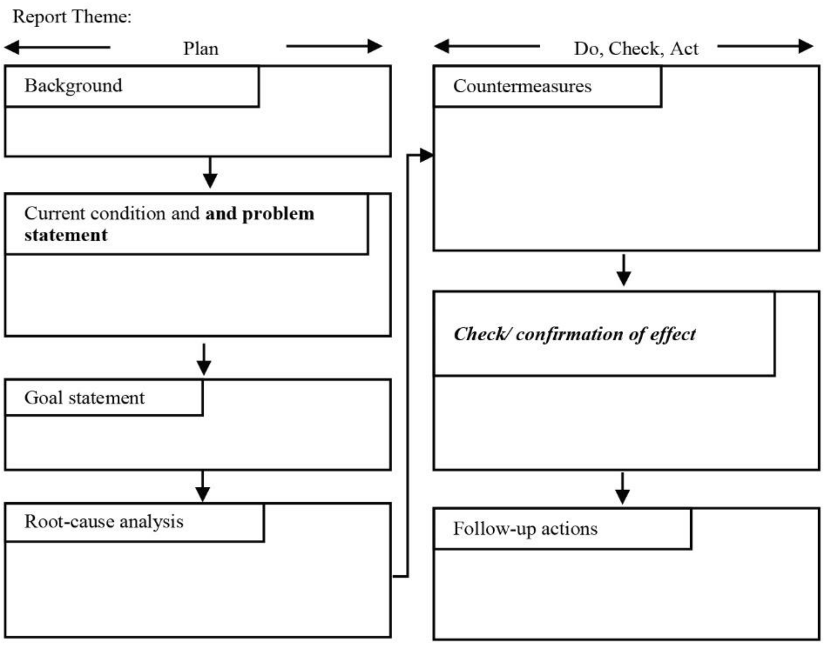



**Figure 2-6. An example of the A3 report (Sobek II & Smalley, 2011)**

#### 2.7.1.2 Summary of Continuous Improvement and its Tools

CI is an organisation-wide process by which small incremental steps are taken to improve the performance. The establishment of the PDCA cycle and the standardisation are the basis of CI. Expert task force and organic CI are two prevailing organisation designs for CI. In the former, a temporary task force comprising of members from different backgrounds are involved in a project from early stages to the end. The latter consists of a permanent multifunctional work group that sets policy for improvement activities and undertake them across the organisation. The A3 report is a process based on the PDCA cycle for implementing Kaizen. It is an A3-sized sheet of paper comprising seven sections, namely: background, current condition and problem statement, goal statement, root cause analysis, countermeasures, check/confirmation of effect, and follow up actions.

#### 2.7.1.3 Discussion

In order to improve tolerance management and proactively prevent defects associated with tolerances, it is important to integrate CI into the practice of tolerance management. To do so, one approach can be to design a solution for tolerance management which is based on the PDCA cycle. The other approach is to use a CI tool such as A3 reports in such solution.

### 2.7.2 Organisational Design for Tolerance Management

A successful integration of CI into regular activities requires development of an appropriate organisational design (Berger, 1997; Imai, 2012). Moreover, tolerance management should be studied within an organisational context rather than focusing on activities individually (Jingmond & Ågren, 2015; Krogstie, 2015). Hence, it is important to understand the possible organisational design that can facilitate integration of CI into tolerance management. Two of the prevailing organisation designs for kaizen are known as expert task force CI (Berger, 1997) and organic CI (Audretsch, Martínez-Fuentes, & Pardo-del-Val, 2011; Berger, 1997; Imai, 2012; Lillrank, Shani, & Lindberg, 2001). However, neither of them have been specifically used in the context of tolerance management. A review of the literature in manufacturing reveals that Graves and Bisgaard (1999) propose an organisational design in the context of tolerance management in which CI is an integral factor. Their proposed organisational design is explained in this section.

In their paper, Graves and Bisgaard (1999) suggest a committee framework comprising two levels, strategic level and tactical level. This is to (a) facilitate the negotiations evolving around tolerances, and (b) continually improve the practice of tolerance management over time. At the strategic level, it is proposed to establish a company-wide tolerance management policy coordination board. Such a coordination board deals with the long-term planning for tolerance management and making policy. It consists of members from all professionals and should only deal with high level issues and should not be dealing with project-based tolerance issues. Moreover, it is suggested to establish a tolerance management committee at a tactical level. Such a committee is envisioned to coordinate tolerances in detail and inspect tolerances at a project level. It consists of representatives from the design team, the quality control team, and from the manufacturing team. Note that the Tolerance Committee has a flexible structure and whenever a particular project participant is needed, they should be invited to join the committee.

The responsibilities of the tolerance committee at a strategic level are as follows (Graves & Bisgaard, 1999):

- **To establish** a policy for a definitive tolerance management practice across the company;
- **To designate** an authority for specifying tolerances and making exceptions;

- **To maintain** a data base for previous experiences. The data base, called tolerance manual, includes a record of assigned tolerance values, measurement results, tolerance problems occurred and solutions to fix those problems. Also, tolerance manual includes any document that is related tolerance management;
- **To mediate** large-scale disputes due to tolerance problems;
- **To ensure** the practice of the organisation for tolerance management is continually improving.

The responsibilities of the tolerances committee at a tactical level are as follows (Graves & Bisgaard, 1999):

- **To implement** the company's policy on tolerance management at a project level;
- **To identify** tolerance risks;
- **To assign** tolerances and get them approved by the company-wide Tolerancing Board;
- **To facilitate** discussions between parties regarding tolerances;
- **To mediate** disputes due to tolerance problems.

#### 2.7.2.1 Summary of Organisational Design for Tolerance Management

In terms of the organisational design to integrate CI into the practice of tolerance management, it is suggested to have two committee frameworks: one at the strategic level and one at the tactical level. The strategic tolerance management committee consists of members from all professionals and deals with long term planning for tolerance management and making policy across the company. On the other hand, the tactical tolerance management committee coordinate tolerances at a project level.

#### 2.7.2.2 Discussion

Close inspection of the proposed organisational design shows that it has the potential to establish the PDCA cycle and to standardise the basis of CI in the context of tolerance management in construction. The tactical tolerance committee involves the project members with different roles. This is in line with the suggestion given for tolerance management in construction (American Concrete Institute, 2014; Ballast,

2007) and in manufacturing (Dantan et al., 2003; Marguet & Mathieu, 1998; Thornton, 2004). Then, the tolerance committee at a strategic level come into play and ensures the knowledge gained in each project is maintained in a data base and is disseminated across the organisation. This is especially useful because members of tolerance committee at a strategic level are fixed and can maintain the best practice of tolerance management in all projects. In theory, it seems that the proposed organisational design has the potential to be used for tolerance management in construction. Such organisational design is expected to reduce tolerance problems encountered due to temporary multi-organisations by offering a consistent process during the project's lifecycle (adopted from Kagioglou, Cooper, & Aouad, 1999).

### *2.7.3 Risk Management*

Risk management is a key to the success of tolerance management (Shahtaheri et al., 2017). Risk management in the context of tolerance management should foresee tolerance problems and develop appropriate countermeasures to eliminate or reduce their adverse impacts (American Concrete Institute, 2014; British Standards Institution, 1990; Shahtaheri et al., 2017). This section explores the concept of risk management and tolerance risks.

#### 2.7.3.1 Definition and Classification of Risk

Risk can be defined as "the exposure to the chance of occurrence of events adversely or favourably affecting project objectives as a consequence of uncertainty" (Al-Bahar & Crandall, 1990, p. 534). A risk may have several causes and similarly may have more than one impact if it occurs (PMI, 2013). The process of risk management is important in construction and the risk classification is a critical step in that process. The risk classification aims at structuring the various risks that can affect a project. Tah and Carr (2001a) classify risk using the hierarchical risk-breakdown structure (HRBS). In this method, risks are divided into two categories: internal and external. The external risks compared to the internal risks cannot be controlled proactively. The external risks include economic, physical, political, and technological changes. There is a need to monitor and predict the external risks. The internal risks are relativity controllable but vary between projects (Tah & Carr, 2001a).

#### 2.7.3.2 Risk Management Process

Although every construction project is different and each should be considered afresh, the process of risk management comprises a fixed set of techniques that can be applied to any project (Flanagan & Norman, 1993). Hence, a good management of a project must incorporate an effective risk management in the form of a standardised process (Haimes, 2009). Having reviewed the literature, the steps below were found for an effective risk management process:

- Risk identification;
- Risk analysis and evaluation;
- Response management.

A detailed description of the steps of the risk management process is presented in Appendix E.

#### 2.7.3.3 Tolerance Risks in Construction

Alshawi and Underwood (1996) state that, in general, tolerance risks in the connections between the cladding/blockwork/brickwork and structural frame are likely to occur. A list of common tolerance risks in construction in is given in (British Standards Institution, 1990). It is important to recognise and minimise those risks at early stages of the project. The most common and typical tolerance risks are as follows (British Standards Institution, 1990):

- **Concrete floors**: The level and flatness of flooring are important. The level is influenced by the thickness of in situ flooring and the flatness of surfaces depends on the construction method;
- **Roof deckings**: The design of a roof should allow for manufacturing deviations, deviations in the sizes and form of the roof, deviations in positions of supports, and deviations in the size and position of roof lights;
- **Stairs**: In the interface between the finish to a stair, tolerance problems are likely due to deviations in the storey height, and in the dimensions of the stair flight;
- **Lift wells**: Tolerance problems in lift wells are common. The problems may arise due to (a) deviations in the size and position of the structural openings in concrete walls and the lack of fit between the concrete walls and lift wells, (b) misalignment of door openings, (c) deviations in the height of the lift well;

- **Cladding to external walls**: The connection between the cladding and external walls requires special care. Tolerance problems in those connections may occur due to (a) deviations in floor edges and columns, (b) deviations in setting-out, (c) misalignment of the floor edges or columns;
- **Prefabricated partitions**: When partitions are to be fitted between in situ floors and ceilings, tolerance problems may occur due to deviations in the floor and ceiling level;
- **Windows, doors and panelling units**: When windows, door sets or panels are to be connected to pre-formed opening, tolerance problems are likely due to deviations in the sizes and position of openings and components;
- **Pipework**: Deviations in (a) the location of inlets and outlets connected to the structure, and (b) the manufacture of pipework and conduit assemblies may result in tolerance problems;
- **Ductwork**: The accumulation in the size and position of apertures for ducting (e.g. joints, insulation, flanges, cross-overs) may reduce space needed for access to install, operate and maintain equipment.

#### 2.7.3.4 Summary of Risk Management

Risks can be divided into two categories: internal and external. Unlike external risks, internal risks are relatively controllable. Risk management in general has three main parts: risk identification, risk analysis and evaluation, and response management. It was discussed that in the connections between the roof deckings, lift wells, cladding, prefabricated partitions, pipework, ductwork, windows, doors and panelling units, and other components, especially the structure, tolerance problems are common.

#### 2.7.3.5 Discussion

There is a lack of risk management process developed specifically for tolerance management (Shahtaheri et al., 2017). Such risk management process should provide a basis for proactive identification, analysis and evaluation of tolerance risks (American Concrete Institute, 2014; British Standards Institution, 1990; Shahtaheri et al., 2017). Moreover, a classification for tolerance risks is missing in the literature while such classification is critical for an effective risk management.

### 2.7.4 Inspection Plan (Protocol)

The verification of tolerance compliance should be planned when the permitted deviations are decided (American Concrete Institute, 2014). This is because for each type of deviation a particular method of inspection should be used (British Standards Institution, 2011; Puri, Valero, Turkan, & Bosché, 2018) at a particular time during construction. To be more specific, a clear protocol should be established to measure components or sub-assemblies. Such protocol will: (a) avoid confusion about whether the component or sub-assembly in question should be accepted or rejected, and (b) avoid confusion about what the tolerance requirements for components and sub-assemblies are that need to be checked (British Standards Institution, 2011).

Time, type and position of measurement instruments are important factors in such protocol. Time is important because buildings are subject to movement over time and the expected deviations at different points in time may be different (American Concrete Institute, 2014). The positions where the measurement instrument is placed should be also specified, because it impacts the accuracy of the measurement results (British Standards Institution, 2011). The type of the measurement instrument is another important factor, because the accuracy of measurement methods and instruments has a direct relationship with the magnitude of tolerance values (American Concrete Institute, 2014). When specifying tolerances, it should be noted that measurement instruments and methods used to verify tolerance compliance have their own deviations. The deviation of measurement instruments and methods is added to the deviations of other sources of variations (American Concrete Institute, 2014). The accuracy of different measurement instruments can be found in Appendix G.

As far as it is known, the British Standards Institution (1998a) is the only source that provides a partially practical guideline for the types of inspection required for different execution operations on site. Table 2-10 shows the main columns of the inspection plan that are most relevant to this thesis. In the inspection plan, the following information should be incorporated (British Standards Institution, 1998a):

- The inspection method and the required accuracy for it;
- The location, frequency and timing of tests;
- Acceptance criteria.

The definitions for the headings used in the inspection plan are given in Table 2-11.

**Table 2-10. An inspection plan (British Standards Institution, 1998a)**

| DESCRIPTION | WHERE STATED | CATEGORY | INSPECTION OR ACCEPTANCE TEST | INSPECTION OF END PRODUCT: FINAL, INTERMEDIATE OR SAMPLE | WHEN REQUIRED | METHOD TO BE USED | LOCATION AND FREQUENCY OF INSPECTION | ACCEPTANCE CRITERIA |
|---|---|---|---|---|---|---|---|---|
| | | | | | | | | |

**Table 2-11. The terms and corresponding definitions used in the inspection plan (British Standards Institution, 1998a)**

| TERM | DEFINITION |
|---|---|
| Description | In this column, the element (or better to say feature) (e.g. dimensions of fabricated components) that should be measured is specified. |
| Where stated | This column directs users to the corresponding standard and section. |
| Inspection – final, intermediate | Intermediate inspection, is often performed once an intermediate process (e.g. fabrication) is completed. No definition has been given for the end product inspection but the term implies that this inspection should be done when the entire work is completed. |
| When required | The options available for completing this column are: 'always', 'always when occurs', and 'when stated in project specification'. |
| Methods to be used | In this column the type of instrument is specified. |
| Location and frequency of inspection | The timing, frequency and position of inspections should be defined. |
| Acceptance criteria | The options given for completing this column are: (a) to state a particular section in a reference document, or (b) writing 'as stated in project spec'. |

#### 2.7.4.1 Summary of Inspection Plan

It is important to plan the verification of tolerance compliance proactively in advance. Especially, time and position of measurement instruments are important in the plan. The inspection protocol suggested by (British Standards Institution, 1998a) can be potentially used to plan the tolerance compliance measurement. In this protocol, first the description of the element to be measured should be written. This column can be potentially used to describe the type of tolerance on a particular component or in a sub-assembly. In this protocol, the reference document from which tolerance requirements are adopted should be detailed. The intermediate and final inspections imply the need to clearly state whether the measurement should be carried out between or after the completion of the work. The instrument by which measurement is carried out should be stated. The frequency of measurement and the location of measurement instrument should be specified. Last, in such a protocol, it is necessary to specify the acceptance criteria against which either deviations are accepted or not.

#### 2.7.4.2 Discussion

One of the root causes of tolerance problems identified in the literature is poor tolerance compliance on site (Bradford, 2017; Jingmond & Ågren, 2015; Seymour et al., 1997) and one of the recommendations in the existing tolerance management mechanisms is to create a measurement plan for tolerances (Ballast, 2007; Precast/Prestressed Concrete Institute, 2004). The literature in construction and manufacturing states the importance of having such plans for tolerance management. However, no exact practical guide could be found in the literature about how to produce a measurement plan for tolerances.

## 2.8 Communication of Tolerance Information

All parties must have an adequate understanding of tolerance information (American Concrete Institute, 2014; Graham & Lindholm, 1978). Tolerance information should be communicated properly between parties to improve the uniformity in the decisions and the effectiveness of decisions made for the required accuracy (Alshawi & Underwood, 1996; British Standards Institution, 2009b). However, ineffective communication of tolerance information is a long-standing problem in the industry and insufficient attention has been devoted to the communication of such information (Anderson, 1965; Ballast, 2007; Milberg, 2006; Savoini & Lafhaj, 2017). Note that the exchange of tolerance information is essential to ensure that components fit and function properly (Krogstie et al., 2015). Currently, two of the main means to communicate tolerance information are via specifications and drawings (Alshawi & Underwood, 1996; Ballast, 2007). The ways by which tolerance information on specifications and drawings are communicated are presented next.

***Communication of Tolerance Information on Specifications***

Construction specifications often include a section containing a list of applicable reference documents (Frank, 2012). Nevertheless, such reference documents are listed unsystematically (Frank, 2012). In other words, the listed reference documents are not necessarily relevant to the project and it is not a common practice to filter through the reference documents that may apply (Frank, 2012). Therefore, it is often left up to the contractors to translate the relevance of reference documents (Frank, 2012). The architects and contractors often consider this list of reference documents as a means to protect themselves in case of serious disputes (Ballast, 2007).

Having an all-inclusive list of reference documents in specifications, most of which are not pertinent to the work, does not mean that designers and construction trades are aware of the purpose of all of them (Frank, 2012; Smith, 2010). Interestingly, parties, even those who actually prepared the specifications, do not read the listed reference documents, yet the contractor must be thoroughly aware of the requirements stated in reference documents (Frank, 2012). The responsibility of understanding all the listed reference documents and deciding which reference documents need to be applied in specific instances is passed to the last trade in a chain of activities during design and construction; the trade who is probably least able to perceive the requirements given the intricacies of reference documents (Frank, 2012; Smith, 2010).

***Communication of Tolerance Information on Drawings***

Dimensions are used in all types of design documents to specify size, location and orientation of features of each component (Hayes, 2014). Architects and engineers typically use chain dimensioning, in which all dimensions in their drawings are connected head-to-tail as chains and do not specify tolerances (Hayes, 2014). Ballast (2007) argues that the existing methods to communicate tolerance information on drawings are ambiguous and increase the probability of tolerance problems. It is common practice to adopt dimensions from reference documents and replicate them for upcoming projects without considering tolerances (Hayes, 2014), whereas the construction teams assume that tolerances have been taken into account by designers (Ballast, 2007).

Designers sometimes distinguish between important from less important dimensions using the term ‘HOLD’ (although other terms are also used). This is to imply that tolerances of a dimension is important. They may also use plus and minus sign (±) as a prefix or suffix to emphasise that there will be variation (Ballast, 2007). However, the exact amount of permitted deviation is not stated and communicated in either of these methods.

Moreover, tolerances can be communicated on drawings using the conventional plus/minus method in: (a) a local or general note that constitutes provision for standard tolerances, (b) in the caption of the figure if tolerances apply to all sizes, or (c) adjacent to a particular size (British Standards Institution, 1999, 2013; Savoini & Lafhaj, 2017). The conventional plus and minus approach can be useful because: (a) it results in the simplicity of the communication of tolerances, and (b) it leads to a lower risk of misunderstanding about the tolerance values (Holbek & Anderson, 1977). Moreover, Ballast (2007) suggests that the position of components should be specified in relation to datum points. It is important that datum points are not in line with the component that its position is specified.

The British Standards Institution (1999) suggests that tolerances should be specified on a drawing if there is a functional requirement to control size, form or orientation. However, it does not provide any particular method to: (a) distinguish between these types of tolerances, and (b) specify them. For example, clearances are one of those areas that should be toleranced. It is common practice to show clearance with fixed dimensions. However, given that the purpose of the provision of clearances is to accommodate variations, in reality the size of the clearances is variable. It is important to communicate tolerance values in clearances for the purpose of compliance measurements on site (British Standards Institution, 2013).

### *2.8.1 Summary of Communication of Tolerance Information*

In an effective practice of tolerance management, tolerance information (e.g. the class of tolerances and the methods to verify tolerance compliance) should be communicated between parties. However, the communication of tolerance information is a long-standing problem in the industry as there is no standardised and widely accepted method for it. Currently, there are two main means to communicate tolerance information: specifications and drawings. Specifications often include a list of reference documents which are not necessarily pertinent to the project and even those who have prepared the specifications are not always aware of their content. Moreover, the existing methods to communicate tolerance information on drawings (e.g. plus and minus approach) are ambiguous and ineffective.

### *2.8.2 Discussion*

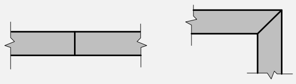
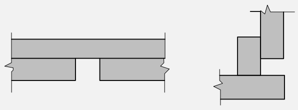
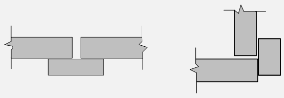
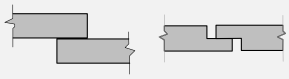
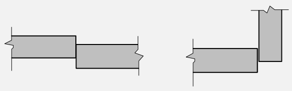
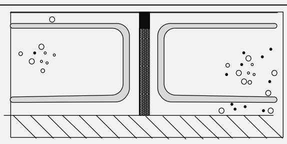
Communication of tolerance information is of prime importance. Two methods exist for such communication: specifications and drawings. However, it appears that no specific approaches have been suggested to communicate tolerance information in specifications, and as a result, specifications constitute a list of reference documents, not all of which are even relevant to the project. Some methods have been suggested to communicate tolerance information in drawings, for example the use of local notes, but one may argue that how those suggestions should be exactly applied in practice.

In other words, there is no any standardised method of communication of tolerance information in specifications and drawings.

## 2.9 Design of Appropriate Connections

The appropriate design of connections is one of the approaches that is necessary for managing tolerances because connections are one of the main means to accommodate deviations (Alexander, 2014; Ballast, 2007; British Standards Institution, 1990). Those connections, called movement joint or flexible joint (i.e. the movement connection or the flexible connection), are provided within the structure or between components (e.g. partitions and services) (Alexander, 2014; Ballast, 2007; British Standards Institution, 1990; Bussell & Cather, 1995; Smith, 2010). There are different types of connections that can be designed but in the context of tolerances, the butt, concealing, and covered connections are the most prevailing ones (Ballast, 2007). The connections are explained in Table 2-12. In this Table, all illustrations except the one for expansion connection have been adopted from Ballast (2007). The illustration for the expansion connections has been adopted from Russ and Cather (1995).

**Table 2-12. Most commonly used connections in the context of tolerances, their descriptions and figures**

| TYPE OF CONNECTION | DESCRIPTION | ILLUSTRATION |
|---|---|---|
| Butt connection | When two components are at a miter connection and no movement is envisioned, this type of connection can be used (Ballast, 2007; Smith, 2010). |  |
| Concealing (reveal) connection | This type of connection accommodates: (a) minor variations in the position of components which results in misalignment, and (b) some variations due to building movement (Ballast, 2007). |  |
| Covered connection | This connection can accommodate either small or large variations (e.g. variations due to building movement). It can be also used when there must be a clearance between two components (Ballast, 2007). |  |
| Sliding connection (also known as a half-connection) | This connection accommodates large variations in the size and position of components and variations due to building movement (Alexander, 2014; Ballast, 2007; Smith, 2010). |  |
| Offset connection | This connection can accommodate minor variations due to building movement (Ballast, 2007; Smith, 2010). |  |
| Adjustable connection | Components must be positioned precisely and therefore it is important to have a mechanism by which the components can be aligned in despite of deviations in positions (Smith, 2010). To solve misalignment problems, adjustable connections (e.g. oversized holes, and horizontally or vertically slotted anchors) can be used (Smith, 2010). | |
| Expansion connection | This connection accommodates variations due to building movement caused by the expansion of components (Bussell & Cather, 1995). |  |

## *2.9.1 Summary of Design of Appropriate Connections and Discussion*

The design of appropriate connections is one of the recommendations given for tolerance management in construction (American Concrete Institute, 2014; Ballast, 2007; British Standards Institution, 1990; Precast/Prestressed Concrete Institute, 2004) and inappropriate design of connections is one of the root causes of tolerance problems (Alexander, 2014; Feld & Carper, 1997; Williams, 2007). The most prevailing connections that have the potential to accommodate variations and, therefore, can be useful for tolerance management are: expansion, adjustable, sliding, covered concealing and butt connections. The selection of connections should be based on the type of variations as each of them is capable to accommodate particular sources of variations.

## 2.10 Terminologies Used for Tolerance Management in Manufacturing

It was discussed in Section 2.6 that one of the root causes of tolerance problems is the lack of terminology in the construction management body of knowledge to communicate tolerance information (Brookes, 2005). Milberg (2006) presents several terms related to tolerances used in GD&T with the aim of adopting them for construction. However, it is not evident which of those terms are more applicable to construction and how they can be refined and adopted for construction. Hence, GD&T is reviewed to seek for terms that can be specifically used for this purpose. Moreover, having reviewed he literature in manufacturing, the author realised that there is another term which is commonly used in the manufacturing literature and can potentially be adopted for tolerance management in construction, namely Key Characteristic (KC). In this section, first the terms in GD&T are explained and explored and then KC is defined.

### *2.10.1 Geometric Dimensioning and Tolerancing*

GD&T is a symbolic language (Henzold, 2006; Stites & Drake, 1999) that specifies the permitted variation in size, form, orientation, and location of features (i.e. size or surface) on a component (Fischer, 2011; Krulikowski, 2012). GD&T conveys the design intent regarding tolerances not only by defining the size and shape of the component, but by also representing the relationship between components in an assembly using datum (Miller, 1994). Datum is defined as a theoretically exact point, axis, or plane from which the location or geometric characteristics of a feature are established (Henzold, 2006).

Geometric characteristics and their associated symbols are the essence of GD&T. The scope of this thesis disregards the symbols and only covers a set of five characteristics. Table 2-13 shows these characteristics to fall into three tolerance types (categories): (a) Form, (b) Orientation, and (c) Location. It is worth noting that in the main version of GD&T, there are five categories. The fourth category is the Runout tolerance that is applied to rotating parts. When buildings have rotating parts (e.g. a revolving restaurant), the tolerancing of those parts are expected to be handled by mechanical engineers. Hence, this category and its two symbols do not seem to have relevant application in construction. The fifth category is the Profile tolerance. This category is excluded because it can be indirectly controlled by other categories (Krulikowski, 2012). The author of this research deemed the other seven characteristics, namely Circularity (roundness) and Cylindricity under the Form category, Concentricity, and Symmetry under the Location category, and Angularity under the Orientation category (The American Society of Mechanical Engineers, 2009) are less applicable in the construction industry and therefore, they are excluded from the scope of this thesis. Because (a) there is not much need for them given the nature of assemblies in construction and the purpose of the symbols, and moreover (b) they can be indirectly controlled by other GD&T characteristics (Krulikowski, 2012). A summary of categories, characteristics and rules related to datum in GD&T is given in Table 2-13.

**Table 2-13. Summary of types of tolerances, characteristics, and rules related to datum in GD&T (Krulikowski, 2012)**

| TYPE OF TOLERANCE | CHARACTERISTICS | DATUM REQUIRED |
|---|---|---|
| Form: It establishes the shape of a surface. | Straightness: It represents how straight a surface is on along a line. | No |
| | Flatness: It demonstrates the amount of deviation of flatness that a surface is allowed to have. | No |
| Orientation: It describes the relationship between features and datums at particular angles. | Perpendicularity: It limits the amount of variation allowed over a surface or axis from being perpendicular to the datum plane. | Yes |
| | Parallelism: It limits the amount of variation allowed over an entire plane, from being parallel to the reference plane. | Yes |
| Location: It establishes the position of the feature relative to a datum. | Position: It determines the deviation of a feature's axis from the true position. | Yes |

### 2.10.1.1 Summary of Geometric Dimensioning and Tolerancing

GD&T is a universally recognised language and nomenclature throughout the design, manufacturing and inspection process. Such unification is requisite for communicating the design intent downstream and ensuring the functionality of assemblies exists without any ambiguity. In this thesis, three tolerance types (i.e. Form, Orientation, Location) and five characteristics (i.e. Straightness, Flatness, Perpendicularity, Parallelism, Position) are covered.

### 2.10.2 Key Characteristics

KC in the context of tolerance management is defined as a property of a product that is needed for that product to function properly. Such KC should be in the risk of not being obtained due to dimensional and geometric variations (Marguet & Mathieu, 1998). In fact, tolerance management can be improved by tightening tolerances on the KCs of components (Marguet & Mathieu, 2003). In a broader context, a KC is defined as a "quantifiable feature of a product or its [sub]-assembly … whose expected variation from target has been unacceptable impact on the cost, performance, or safety of the project" (Thornton, 2004, p. 35).

KCs are defined by customer requirements and are systematically flowed down from assemblies to subassemblies and then individual products (Marguet & Mathieu, 1998; Thornton, 2004). A sub-assembly comprises of a set of KCs that need to be satisfied.

In order to identify KCs, the major functional requirements that may be affected by dimensional and geometric variations should be identified. Such functional requirements should be recognised at the early design stage and acceptable variations should be assigned to them (Marguet & Mathieu, 2003).

#### 2.10.2.1 Summary of Key Characteristics

KC is a prevailing term used in the manufacturing literature. KC is any property of a product that is necessary for the function of that product and it can be affected by dimensional and geometric variations.

#### 2.10.2.2 Discussion

Four characteristics, namely Straightness, Flatness, Parallelism, Perpendicularity and Position were identified from GD&T. Based on their definitions, these characteristics can potentially be used in construction. Straightness can be used to communicate the deformation of beams and columns due to loads. Flatness can be used to present the flatness of a floor surface. Flatness can be used when two surfaces should maintain a constant distance. Perpendicularity can be used to ensure that a surface or axis is exactly at a right angle. Position can be used to control the location of a feature of size (e.g. columns and beams).

Having defined critical dimensions (explained in Section 2.2), KCs and characteristics in GD&T, one may argue the difference between these terms. As far as it is known, there is no linkage between these terms in the literature. However, according to the definitions, it is perceived that critical dimensions and characteristics used in GD&T are a subset of KCs. This is because a KC can be any feature on a product or sub-assembly, whereas a critical dimension is only limited to dimensions as its name implies. Also, a characteristic is categorised as a KC when its variation from the target value can result in unacceptable impact on cost, function and safety of assemblies. In the construction context, the flatness of concrete slabs is a characteristic but may not be necessarily a KC because deviations in the flatness may not necessarily impact on the function and safety of concrete slabs and may not necessarily require costly modifications. The use of the term KC in tolerance management in construction seems appropriate particularly to distinguish between characteristics with or without adverse impacts.

## 2.11 Summary

Many topics are covered in this chapter because the chapter contributes to both understanding the problems and developing the solution. Moreover, the proposed artefact (i.e. the Tolerance Management System) is expected to be holistic and start from early stages of the project and continue to completion. The review of the root causes of tolerance problems in the literature is essential to understand the problem with the current practice of tolerance management. The review of the processes, recommendations and concepts relevant to tolerance management not only in construction but also manufacturing helps to develop a solution which will effectively tackle the identified root causes.

# CHAPTER 3: RESEARCH METHOD

In this chapter, the research method adopted in this thesis is delineated and the reason behind the selection of Design Science Research (DSR) as the research method is presented. The features, output and process for implementing DSR are outlined. The research strategy developed for this study is presented along with descriptions of the empirical studies carried out during the study. The process taken to develop the solution to improve tolerance management is demonstrated in this chapter.

## 3.1 Justification of the Design Science Research in this Research

In this section, the reasons why DSR has been selected for this thesis are justified. The choice of research method is important because an adequate method ensures the rigour of the research work (Dresch et al., 2015; Saunders, Lewis, & Thornhill, 2016). As discussed in Chapter 1, tolerance is a problematic issue in the construction industry. Tolerance problems are recurring and are often mitigated at the time and place of the construction process reactively and the way they are resolved, to a great extent, hinges on the labourer's experience. However, there is not currently much academic-based knowledge on how to proactively manage tolerances.

There is a need for further research in tolerance management from both theoretical and practical viewpoints. To date, the literature has mostly focused on exploring the problem with tolerances using traditional research approaches, such as questionnaire surveys and interviews, without or with limited empirical studies (Forsythe, 2006). There are sources (e.g. American Concrete Institute, 2014; British Standards Institution, 1990; Davison & Owens, 2012; Price et al., 2019) that extol any improved tolerance management for its ability to minimise defects but do not offer any considerable actionable advice (Bradford, 2017; McCarney, 2017; Milberg, 2006). All in all, from a theoretical viewpoint, the existing research has not yet provided sufficient knowledge about improving tolerance management, it is based on the participants' perspective rather than empirical studies, and gives limited practical recommendations. From a practical viewpoint, there is evidence that tolerance issues are a practical problem that need to be resolved (Bradford, 2017; McCarney, 2017; Milberg, 2006).

Two research paradigms exist in the literature, namely 'positivist' approach and 'interpretivist' approach that often represent two extremes on a continuum (Holden & Lynch, 2004). Positivist is described as objective, quantitative, traditionalist and scientific in nature. Interpretivism is often categorised as subjective, qualitative, phenomenological or humanist (Collis & Hussey, 2013). However, these descriptions are broad and cover terms that are used sometimes for contradictory approaches (Halfpenny, 2014). Halfpenny (2014) argues that "controversy over positivism begins immediately…because there are so many different understandings about how the term can or should be used" (p.11). Likewise, the same principle applies to interpretivism. In the context of tolerance management, there are examples of prior research that mainly adopt the positivist approach (e.g. Milberg, 2006; Rausch et al., 2017; Vorlíček & Holický, 1989), that is, they are meant to be more objective by involving more engineering aspects of tolerance management and performing more empirical studies (e.g. site observations), and some mainly adopt the interpretivist approach (e.g. Alshawi & Underwood, 1996; Bradford, 2017), that is, they are meant to be more subjective as they are based on the perceptions of the participants.

DSR is a set of analytical and synthetical techniques to undertake research that complements the positivist and interpretive perspectives (Vaishnavi, Kuechler, & Petter, 2004). The key tasks of DSR are (a) to construct an artefact which will address the practical problems by its developed applicable solutions (Hevner et al., 2004), and (b) to bring together two realities: practice and theory (van Aken, 2005). DSR is a scientific problem-solving process and follows several steps to generate an innovative and useful artefact, which makes a contribution to knowledge. Several research works such as Kemmer (2018) and Dave (2013) demonstrated that DSR is an appropriate research method in construction management, especially when the aim is to develop solution artefacts for practical problems with the ultimate aim of implementing such solution in construction. DSR is thus selected for its capability to contribute to both the existing academic knowledge and to solve practical problems, focused towards preventing tolerance problems proactively and avoiding their future reoccurrence. This research through the use of DSR aims to provide a middle ground between positivist and interpretive by providing an ability to generalise the gained knowledge, accepting direct involvement of researcher in the research, and being able to make the research both subjective (e.g. developing the solution based on the researcher's creativity) and objective (e.g. developing the solution based on the empirical studies). DSR allows the flexibility of using a wide range of research tools (Dresch et al., 2015), and a means to devise a solution and evaluate it

(Hevner et al., 2004; Kasanen et al., 1993; Koskela, 2008; Vaishnavi et al., 2004; van Aken, 2005).

### *3.1.1 Comparing Design Science with other Methodologies*

A comparison between DSR and traditional science methods, action research and case study is presented in this section.

#### 3.1.1.1 Design Science versus Traditional Sciences

Traditional sciences, such as natural and social sciences, lead to studies that focus only on explaining, describing, exploring, or at the most predicting phenomena and identifying their relationships with each other (van Aken, 2004). Nevertheless, the traditional sciences have limitations when the objective is to undertake problem-solving research or to construct a new artefact that does not already exist. As a result, traditional sciences have been criticised for such limits (March & Smith, 1995), because understanding a problem as such often is not sufficient to solve it (van Aken, 2005).

Given the topic of tolerance management has not been well-researched yet, it is important to document the current practice of managing tolerances and to explore the nature of tolerance problems. However, exploring, describing, and explaining are not sufficient, and the research in this field should be able to eventually design a solution to solve the problem. This PhD research aims at creating a new artefact called TMS. This means that the focus of this research is not only on understanding and describing the problem, but it also aims to solve a real-world problem and construct a new artefact that can improve the existing practice of the construction industry. In other words, the formal sciences and the explanatory sciences are not adequate and the use of DSR is recommended because it intends to propose ways of constructing and evaluating artefacts with certain properties (Walls, Widmeyer, & El Sawy, 1992).

#### 3.1.1.2 Design Science versus Action Research and Case Study

Case study and Action Research (AR) were considered initially as potential approaches for undertaking this research. These two approaches were considered because of their ability to explore and understand a practical context being studied. Case study should be chosen as the research method when describing, explaining and exploring a complex contemporary phenomenon (Dubé & Paré, 2003; Yin, 2013). AR combines researcher intervention with theory generation to solve problems in organisational contexts (Khan & Tzortzopoulos, 2016). Like case study, AR is descriptive, exploratory and explanatory. Nevertheless, unlike the case study, when deploying AR as a research method, the researcher has to actively cooperate with the target organisation and there must be an involvement between the members of the target organisation and the researcher, and the researcher cannot be only an observer (Morandi, Rodrigues, Lacerda, & Pergher, 2014).

Moreover, Järvinen (2007) argues that DSR and AR are similar research approaches. However, Iivari and Venable (2009) argue that DSR and AR are decisively dissimilar. DSR does not focus on any specific client or collaboration between the researcher and client and the DSR solution aims at solving a class of problems.

Despite the focus of these two research methods, case study and AR, is on the understanding of a complex phenomenon such as the one being investigated in this research, none of them are appropriate to attain the objectives of this research, that is to create a new artefact to improve the current practice of tolerance management. More specifically, the focus of this research is not only on understanding and describing the problem, but it also aims to solve a practical problem and construct a new artefact that can improve the existing practice of the construction industry in terms of tolerance management. In addition, given that the researcher is not focused on solving a problem of any particular client, AR seems to be inappropriate. All in all, case study and AR did not seem appropriate for this research due to the reasons described.

## 3.2 Design Science Research

According to van Aken (2005), one of the reasons for the gap between academic research and the practitioners needs is that the research works sometimes do not generate knowledge that can be directly used in practice. Another problem with traditionally used research methods is that organisations can become discouraged by being asked for surveys, observations, and interviews without any feedback and benefit to them. Practitioners are questioning the benefits and outcome of being asked to attend such field studies and academic analyses. On the other hand, academic research needs acceptance from the academic community and, therefore, it should also be concerned with rigour (Hatchuel, 2009). Note that rigour supports relevance and relevance is a prerequisite of rigour (Hatchuel, 2009), but relevance as such is not sufficient for research to be considered rigorous. In fact, suitable and adequate research methods and data collection tools are required to develop academic knowledge (Dresch et al., 2015).

This research has adopted DSR, which has the mission of not only bridging the gap between theory (i.e. academic knowledge) and practice, but to also contribute to the existing theories (van Aken, 2004). Hence, DSR in this study was selected to bring both the rigour and relevance to the research. The researcher established a two-way communication and close teamwork with the study organisations The researcher was communicating the existing knowledge and developed solution to those organisations in the form of presentations and reports. This was expected to contribute to improving the performance of target organisations, as they often do not update themselves with the recent knowledge on their own (Lukka, 2003). The teamwork between the study organisations and researcher resulted in the construction of the solution artefact, which is Tolerance Management System.

## 3.3 Design Science Research Process

Koskela (2008) discusses that DSR is about building and evaluating, which means designing and constructing an artefact, and ensuring that the identified problem has been solved. The artefacts are created with the ultimate goal of solving problems, making changes in the application area, and improving performance. The study of artefacts leads to results with a prescriptive nature as they aim at solving problems (Dresch et al., 2015). There are different proposed steps in the literature to undertake DSR. The processes proposed by Kasanen et al. (1993), Alturki et al. (2011), van Aken et al. (2012), and Vaishnavi and Kuechler (2015) were reviewed. The authors propose almost similar steps for conducting research based on DSR. All authors suggest 'problem definition' as a first step for the development of artefact (Alturki et al., 2011; Kasanen et al., 1993; Vaishnavi & Kuechler, 2015; van Aken et al., 2012). The problem definition step is a dynamic step and is not static. This means that when the research moves forward through the problem analysis, the researcher may recognise that the defined problem is still more complex than it was perceived earlier, and the scope of the problem should be narrowed down further. Conversely, the researcher may find that solving the defined problem has more potential for improvement and may enlarge the scope (van Aken et al., 2012). The identified problem should have potential for research and should be relevant to practice (Kasanen et al., 1993; Lukka, 2003). The next step is 'problem awareness', which can arise from different manners (Alturki et al., 2011; Kasanen et al., 1993; van

Aken et al., 2012). The outcome of this step is a proposal for a new research work (Vaishnavi & Kuechler, 2015). The 'suggestion' step is then proposed (Alturki et al., 2011; Kasanen et al., 1993; Vaishnavi & Kuechler, 2015; van Aken et al., 2012). In this step, a new solution is envisaged based upon the configuration of either gained understanding during the study or existing sources (Vaishnavi & Kuechler, 2015). Creativity is an inevitable part of this step (Vaishnavi & Kuechler, 2015). The next step is 'development', in which the tentative design is elaborated and developed into a complete design (Vaishnavi & Kuechler, 2015). 'Evaluation' is an integral step of DSR (Alturki et al., 2011; Kasanen et al., 1993; Vaishnavi & Kuechler, 2015; van Aken et al., 2012). After the artefact is constructed, it is evaluated according to the criteria set out in the proposal. The researcher then analyses the information gained from the feedback of partners (Vaishnavi & Kuechler, 2015). The researcher moves to the final step of the research, 'conclusion' (Alturki et al., 2011; Kasanen et al., 1993; Vaishnavi & Kuechler, 2015; van Aken et al., 2012), when the results are satisfying, although the behaviour of the artefact might still deviate from the assumed performance (Vaishnavi & Kuechler, 2015). The theoretical contributions of the research effort are analysed and are then written up and consolidated (Vaishnavi & Kuechler, 2015). There are two types of theoretical contributions (knowledge): (a) facts that can be applied and are appropriate for various situations or behaviours that can frequently be cited, and (b) subjects requiring further research as they deviate from the predicted behaviour and it is challenging to explain why (Vaishnavi & Kuechler, 2015).

Overall, a close inspection reveals that 'problem definition', 'awareness of problem', 'suggestion', 'development', 'evaluation', and 'conclusion' are repetitive amongst these proposed processes. Moreover, the notion that the research process is not linear, but involves loops, is underlined in the steps presented in the literature (Kasanen et al., 1993; Lukka, 2003; March & Smith, 1995; Vaishnavi & Kuechler, 2015; van Aken et al., 2012). More specifically, the design process comprises of a sequence of activities that produces an innovative artefact. The process of building and evaluating an artefact is carried out in a loop until the final product is perceived as good enough (Vaishnavi & Kuechler, 2008).

In the next section (2.4), the research strategy chosen for this thesis is presented.

## 3.4 Research Strategy

Research strategy is about tailoring the research method to fit the empirical world being investigated (Blumer, 1986). The research method in this investigation is composed of six interdependent steps as illustrated in Figure 3-7. Those steps are similar to the key steps suggested by different authors for DSR process as discussed in Section 3.3. Note that each of those steps includes different research activities and developments.

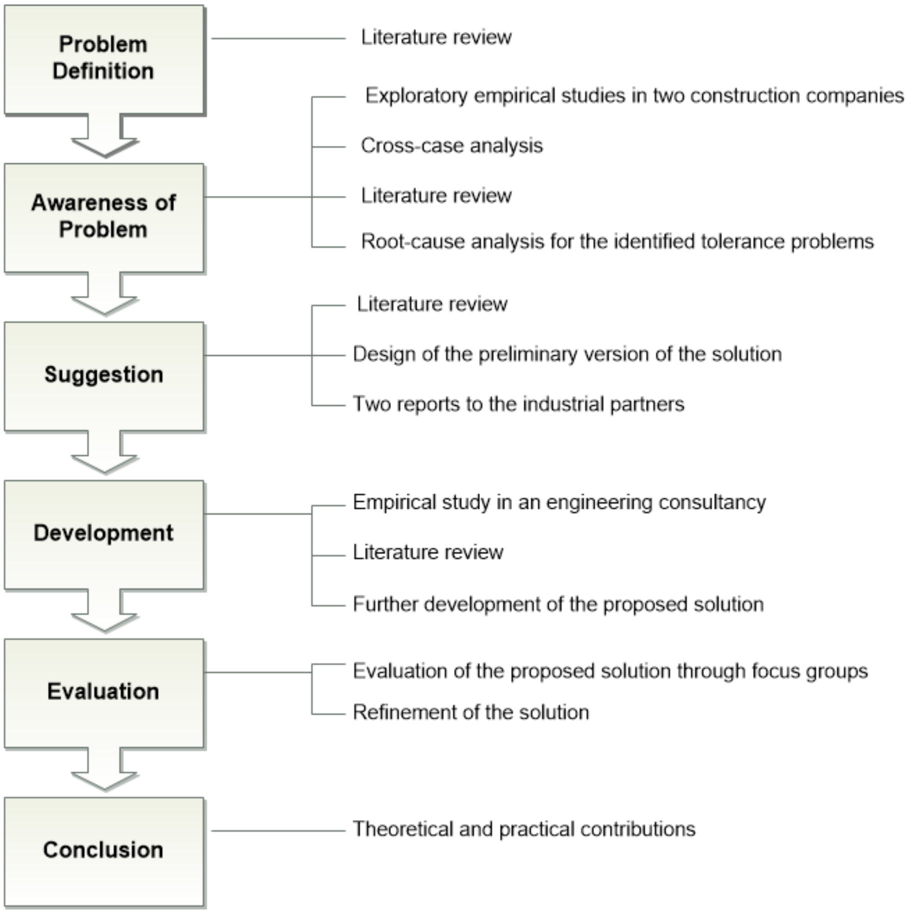



**Figure 3-7. Research process**

### *3.4.1 Step One: Problem Definition*

The first step is about defining a research problem through the literature review. The research problem should have a practical relevance and have a potential for research. A literature review was then carried out not only in the construction project management body of knowledge but also in mechanical engineering and manufacturing literature. Several keywords were used to ensure a thorough literature review has been performed.

The keywords include tolerance, accuracy, precision, deviation, variation, interface management, lack of fit, tolerance problem, dimensional tolerance, dimensional accuracy, geometric tolerance, tolerance compatibility, building movement, dimensional management, tolerance management, variation management and tolerance coordination. The keywords were examined in databases such as Google Scholar, American Society of Civil Engineering (ASCE) Library, Taylor & Francis, Web of Science, Elsevier, Wiley Online Library, EBSCOhost, WorldCat, British Standards Online (BSOL), International Council of Research and Innovation in Building Construction Database, and e-thesis online service (EThOS). The research problem was presented in Chapter 1.

### *3.4.2 Step Two: Awareness of Problem*

This step of the research includes exploratory empirical studies, literature review, cross-case analysis, and root cause analysis. The literature review was carried out to gain a better understanding of the problem identified in the previous step. More specifically, the focus of the literature review in this step was on the literature related to root causes of tolerance problems in order to understand more thoroughly the reasons behind the occurrence of tolerance problems.

Empirical studies were carried out in two construction companies (i.e. case one and case two). The empirical study one was a project, executed by a major contractor in the UK, cost approximately £27.5m and the scheme was to construct a circa 7500 m2 building. The building was to be linked into a recently completed building in two locations. The curvy shape of the building and anodised aluminium fins attached to the structure made the project complex. The project was due to be completed in January 2017, but it was finally completed in April 2017. One of the reasons for such a delay was that ten tolerance problems occurred during this project. The study took place from March 2016 to December 2016. The empirical study two was construction of a terraced warehouse/manufacturing building. The project was to construct a circa 2.30 ha. Five tolerance problems were observed in this case. The study took place from July 2016 to December 2016. The full details of the empirical studies are reported in Chapter 4.

These empirical studies aimed to: (a) understand the mechanisms used to manage tolerances, i.e. how to identify, mitigate and communicate tolerance risks/ requirements, and verify compliance of tolerance requirements, and (b) identify tolerance problems occurred during the empirical studies and their root causes. The empirical studies were essential because the literature on tolerance management in construction appears to be scarce. A combination of data collection tools, i.e. observations, semi-structured interviews, informal interviews and document review were used in this step. The multiple data collection tools results in triangulation which contributes to the rigour (Eisenhardt, 1989), accuracy and reliability of the research (Yin, 2013).

Data collection tools used during empirical studies are described here, followed by a discussion of how they are used in this research. The researcher carried out direct observations in case one and case two. In this type of observation, the researcher does not become an internal member of the case being observed (Yin, 2013). This involves standing in a corner and observing activities in the field, or observing interactions in a meeting, while being unobtrusive (O'Leary, 2004). Taking photographs can be useful because it can delineate the characterises of the case to others (Yin, 2013).

The selection of the companies was based on the following criteria: (a) their acknowledgment of the need to better manage tolerances, (b) their willingness to give the researcher access to their site and to engage their employees in the research, and (c) their type of construction project and the stage of construction in which their project is. It was noticed that participants of case one and two who were approached by the researcher, all acknowledge the consequences of tolerance problems and they gave access to the researcher as they acknowledge a need to improve tolerance management in the industry. Case one was very important because the researcher could observe the installation of curtain walling (frame and glazing), partitioning, fixing of wall tile anchors and mullions, and cladding. The second case were very valuable for the researcher because he could observe the erection of the steelwork from the very beginning, which he could not do it in the first case. As a result, he could understand and observe many issues related to tolerances from erection of the steelwork to the final compliance measurement. The problem with the second case was that given the trades were not as experienced as the trades in the first case, the researcher could not rely on them to make him aware of any tolerance-related problems and he therefore had to visit the site more often to ensure crucial observations were not missed.

The goal of observations in this step of the research was to (a) understand how components are put next to each other and fit is achieved, (b) where tolerances on components, sub-assemblies or clearances become important, (c) how trades achieve the required dimensional and geometric accuracy in in-situ components and sub-assemblies, (d) how trades verify that tolerances requirements have been satisfied, and (e) what tolerance problems are. Moreover, in the second case, the researcher attended ten daily and weekly meetings to understand how tolerance issues are raised, discussed, and sorted.

The researcher visited the site of case one, on average, once a week for half a day during a six-month period from April 2016 to November 2016. The researcher visited the site of case two, on average, for four full days per week for approximately two and a half months from July 2016 to September 2016. The observations included (a) attending discussions with the general contractor, subcontractors, and surveyor to find solutions for the tolerance problems, (b) attending daily and weekly meetings between the general contractor and subcontractors, and (c) observations on site.

Two types of interviews were adopted for this research: semi-structured and informal interviews. In semi-structured interviews, the interviewer follows the interview protocol but questions may not be asked as they were sequenced. The interviewer asks the questions and follows up on points that interviewee makes (Brinkmann, 2013; Roulston, 2010). In this research, the researcher had an interview protocol that differed for each semi-structured interview. The interview protocols were set based on the job title of interviewees. The questions in the protocol were divided between eight sections. The sections represented the type of questions that were asked under such headings. Table 3-14 shows the list of questions and the way that they were categorised in the interview protocol. Such protocols were sent to the interviewees before the interviews took place so they could prepare themselves beforehand. The researcher invited fifteen interviewees with a wide range of expertise to achieve a wide cross-section of opinions on the topic being studied. The interviewees were working in the companies in which the empirical studies were carried out (i.e. case one and case two) and were selected based on their expertise and availability. Table 3-15 and Table 3-16 show the job title of interviewees and key questions in each section in case one and two respectively. The aim of semi-structured interviews was mainly (but not limited) to understand: (a) how tolerance information is communicated, (b) tolerance problems encountered during the empirical studies, (c) root causes of the identified tolerance problems, (d) how tolerance problems can be prevented, and (e) how tolerance management can be improved.

**Table 3-14. Summary of the interview questions**

| SECTION | INTERVIEW QUESTIONS |
|---|---|
| Section A: Tolerances in design | How are tolerances specified?<br>How are tolerances of construction trades coordinated?<br>In what stages of the project should subcontractors integrate the tolerance information into the design of works? |
| Section B: Tolerances on site | What components and connections are problematic regarding tolerances and fitting?<br>What are tolerance-related activities (e.g. connections to absorb deviations) on site? |
| Section C: Tolerance compliance measurement | How do you control the dimensional and geometric accuracy of components and sub-assemblies on the site?<br>How do you ensure that tolerance requirements have been met on the site? |
| Section D: Root causes of tolerance problems | What are the root causes of tolerance problems? |
| Section E: Consequences of tolerance problems | What are the consequences of tolerance problems?<br>What sorts of tolerance issues have the major adverse consequences? |
| Section F: Role of technology | Can Building Information Modelling (BIM) and other technologies (e.g. laser scanner) be useful to better communicate the tolerance requirements (both dimensions and positions)? If yes, how? |
| Section G: Tolerance management process | What is the tolerance management process in your company?<br>How do you coordinate tolerances of different construction trades?<br>How do you ensure that realistic tolerance values are specified?<br>How do you communicate tolerance information with designers and construction trades? |
| Section H: Final Comments | What is missing in the existing practice of tolerance management to effectively coordinate tolerances and prevent tolerance problems? |

**Table 3-15. Summary of the job title of interviewees, the length of interviews and the list of sections of interview questions asked from each interviewee in case one**

| JOB TITLE OF INTERVIEWEES | LENGTH OF INTERVIEWS (MIN) | KEY QUESTIONS | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | SECTION A | SECTION B | SECTION C | SECTION D | SECTION E | SECTION F | SECTION G | SECTION H |
| Project Director | 65 | X | X | X | X | X | X | X | X |
| Design Manager | 127 | X | | X | X | X | X | X | X |
| Architect | 55 | X | | | X | X | X | | X |
| Senior Planner | 59 | X | | | X | X | X | | X |
| Quantity Surveyor | 52 | X | | | X | X | X | | X |
| Quantity Surveyor | 58 | X | | | X | X | X | | X |
| Site Manager | 67 | X | X | X | X | X | | | X |
| Site Engineer | 72 | X | X | X | X | X | | | X |
| Subcontractor | 21 | | X | X | | | | | |

**Table 3-16. Summary of job title of the interviewees, the length of interviews, and the list of sections of interview questions asked from each interviewee in case two**

| JOB TITLE OF INTERVIEWEES | LENGTH OF INTERVIEWS (MIN) | KEY QUESTIONS | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | SECTION A | SECTION B | SECTION C | SECTION D | SECTION E | SECTION F | SECTION G | SECTION H |
| Senior Engineer | 63 | X | X | | X | X | X | | X |
| Senior Surveyor | 46 | X | X | | X | X | X | | X |
| Planning Manager | 37 | X | | | X | X | X | | X |
| Envelope Package Manager | 32 | | X | X | X | X | | | X |
| Senior Engineer | 52 | | X | X | X | X | | | X |
| BIM Strategic Planner | 43 | X | X | | X | X | X | | X |
| Engineer of Concrete Subcontractor | 19 | X | X | | | | | | |

Informal interviews disregard all the formal rules to establish rapport and trust between the interviewer and interviewee. This will lead to a more natural environment and a more open, relaxed communication which can occur at any place at any time (O'Leary, 2004). In his research, informal interviews took place in case one and case two in the form of short conversations, often on site with operatives or in the office with key members of staff. The researcher asked questions about what he was observing on site to ensure that his perception was correct or to find an answer for specific questions that had been raised. This method was very useful for the researcher, particularly to understand the technical aspects of the identified tolerance problems.

The document review was a means of data collection in both cases. The review of documentary information plays a major role in data collection (Yin, 2013), despite documents may not always be accurate (Yin, 2013). Documents can corroborate evidence collected from other sources. They are useful in verifying information about an organisation or project that might have been indicated in other means of data collection (Yin, 2013). In case one, the researcher reviewed the project drawings, architectural BIM model, specifications, meeting minutes, surveys of the site engineer, quality check sheets of the steel, concrete and cladding subcontractors, design responsibility matrix, and the list of services that the architect was entrusted to accomplish. In the second case, the researcher was given the drawings for the steelwork and cladding, structural BIM model, specifications, and survey results produced after checking each step of the steelwork. The researcher was looking for tolerance information in those documents (e.g. information related to connections, construction / manufacturing / fabrication / setting-out / erection / movement tolerances). The aim of such document review was to understand (a) how tolerance information is communicated in such documents, and (b) what documents and information are missing for tolerance coordination between parties.

A cross-case analysis was carried out after completing the empirical studies in case one and case two. The goal of having a cross-case analysis was to understand the similarities and differences between tolerance management-related activities performed in these cases (Yin, 2013). Further details of empirical studies and cross-case analysis can be found in Chapter 4.

A root cause analysis was performed for the tolerance problems identified during the empirical studies. The analysis sought to identify the true root causes of tolerance problems. The reason behind performing the root cause analysis is to establish awareness about the main shortcomings of the current practice of tolerance management based on the empirical studies and literature. There are a wide range of tools and approaches for root cause analysis (e.g. Fishbone diagram, 5 why, Cognitive Mapping, System Dynamics, Bayesian Networks, Markov Chains). One of those commonly used tools is the Fishbone diagram, a graphical tool to explore, sort and display the root causes of problems (Mobley, 1999). The principles of the Fishbone diagram are used in this research to identify root causes of tolerance problems identified during case one and case two. Such principles help to better understand root causes of the problem, perceive the relative importance of different root causes, and recognise the areas where problems lie (Barsalou, 2015). The root cause analysis is presented in detail in Chapter 5.

After completion of the empirical studies and literature review, the researcher could state the problem with clarity, and he could ascertain the importance and relevance of the research problem. The insight gained after completing this step of the research was served as a basis to develop the tentative design of the solution to improve tolerance management.

### *3.4.3 Step Three: Suggestion*

After obtaining an understanding of tolerance management and the problem in this realm, the researcher started to explore more of the existing knowledge. This round of the literature review was more targeted. Identification of existing theories and knowledge in the literature helped the researcher to start designing the solution. A system, TMS, was developed based on the findings from the empirical studies, root cause analysis, cross-case analysis and literature review. The initial solution was reported to the companies in which the researcher had carried out the empirical studies one and two. Note that the version of TMS at this stage was not yet fully complete and developed, and it was not presented in the thesis.

### *3.4.4 Step Four: Development*

The aim of this step was to elaborate and develop the tentative design of the artefact proposed in step four. To do so, the researcher connected with an engineering consultant, who demonstrated a relatively advanced practice of tolerance management. The goal was to understand their process of handling tolerance issues in their projects and then develop TMS further. The consultancy is specialised in the built environment for several years and provides services for civil and structural engineering, infrastructure, and environmental engineering. The consultancy was introduced to the researcher by the interviewees in the first two cases because their tolerance management mechanism was advanced compared with those of their rivals.

The study took place from May 2017 to August 2017. The full details of this case are reported in Chapter 4.

The document review as a data collection means was of vital importance in the third case. The researcher was given documents from six projects. Below is the list of documents that were reviewed in case three and included tolerance information. It is worth mentioning that except the 'Design note (tolerance and deflection report)', none of the other documents were directly dealing with tolerances.

- **Structural report**: The report includes civil, structural and transportation consultancy services associated with the project. The tolerance information in this document was about the anticipated deflection and other types of building movement;
- **Site visit report**: The report describes observations of any defect associated with tolerances;
- **Report of constructed structural members on site**: The report comments on the structural member constructed on site in which there is a defect associated with tolerances;
- **Design note (tolerance and deflection report)**: The design note summarises a study associated with the principle structural implications and wider considerations in connection with the potential anticipated deflection and tolerances.

The semi-structured interviews were conducted in case three. In Table 3-17, the job title of interviewees and key questions asked from them are presented. The main purpose of such interviews was to understand the practice of tolerance management in this case, especially because such practice has not been documented by the consultant. The focus of the literature review in this step was on the literature that is directly relevant to the development of the solution. The review of the literature included the literature in construction, manufacturing and mechanical engineering.

This research consists of three cases, in which qualitative data was collected through observations, interviews and document review. Collection of data should continue until the collection of new data does not add any richness to understanding. This principle is called 'saturation' (Bryman, 2016; Taylor, Bogdan, & DeVault, 2015). The data collected in case one and two was perceived to be sufficient to understand the typical practice of tolerance management in construction as saturation seems to happen. The data collected in case three as well was conceived sufficient to understand a non-conventional view on tolerance management, which complements the solutions identified in the literature.

**Table 3-17. Summary of the job title of the interviewees, the length of interviews, and the list of sections of interview questions asked from each interviewee in case three**

| JOB TITLE OF INTERVIEWEES | LENGTH OF INTERVIEWS (MIN) | KEY QUESTIONS | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | SECTION A | SECTION B | SECTION C | SECTION D | SECTION E | SECTION F | SECTION G | SECTION H |
| Senior Structural Engineer | 68 | X | X | X | X | X | X | X | X |
| Senior Structural Engineer | 49 | X | | X | X | X | | X | X |
| Structural Engineer | 29 | X | | | X | | | X | X |
| Structural Engineer | 35 | X | | | X | | | X | X |

The literature review, the root cause analysis and the empirical study three were instrumental for the development of the proposed artefact, TMS. The literature review provided valuable insights such as the need to have a process with a set of steps, and the purpose of the steps. The root cause analysis provided an understanding about the characteristics of the problem, which was essential for developing an effective solution. The empirical study three provided an understanding of the existing relatively advanced practice of tolerance management. In Section 5.3, it is explained how the root cause analysis, literature review and empirical study three helped develop the artefact, TMS.

### *3.4.5 Step Five: Evaluation*

In order to evaluate the developed solution, the focus group is used in this research. Focus group has drawn attention as a method for the evaluation of DSR projects (Bruseberg & McDonagh-Philp, 2002). It can be used for the refinement of a proposed artefact and evaluation of its utility (Brandtner, Helfert, Auinger, & Gaubinger, 2015; Bruseberg & McDonagh-Philp, 2002).

According to Tremblay, Hevner, and Berndt (2010), there are two types of focus groups that can be used for evaluation of artefacts developed by DSR. The first type of focus group is Exploratory Focus Group (EFG) and the second one is Confirmatory Focus Group (CFG). EFG aims at obtaining quick incremental improvements when developing an artefact (Dresch et al., 2015; Tremblay et al., 2010). CFG should be used when the objective of a focus group is to demonstrate the utility of an artefact in a particular class of problem (Dalrymple, 2007; Dresch et al., 2015; Taras, 2008; Tremblay et al., 2010; Venable, Pries-Heje, & Baskerville, 2016; Wiliam & Black, 1996).

Given the time constraints, two focus groups were held in this research. The focus groups were meant to be both EFG and CFG in nature. More specifically, two focus groups were conducted to demonstrate the utility of the proposed solution, that is, they are categorised as CFGs. Also, the solution was refined and improved after receiving feedback from the participants, that is, the focus groups should be considered as EFGs as well.

The evaluation should be based on appropriate criteria (Hevner & Chatterjee, 2010). The criteria proposed by Checkland (2000), Tzortzopoulos (2004), Hevner and Chatterjee (2010), and Khan and Tzortzopoulos (2016) were used to develop a framework to evaluate the solution developed in this thesis. The developed framework for evaluation (Table 3-18) in this research has three hierarchical levels: (a) criteria, (b) attributes and (c) definition of attributes. The criteria in this framework are usefulness and effectiveness. The usefulness is focused on the capability of the framework to be used to improve tolerance management. The effectiveness addresses the capability of the framework to achieve the objective of the framework while using resources (Tzortzopoulos, 2004). Three attributes fall under usefulness criterion, namely flexibility (Checkland, 2000; Hevner & Chatterjee, 2010; Khan & Tzortzopoulos, 2016; Tzortzopoulos, 2004), practicality (Hevner & Chatterjee, 2010; Khan & Tzortzopoulos, 2016) and applicability (Khan & Tzortzopoulos, 2016). Under the effectiveness criterion, three attributes are fallen, namely efficacy (Checkland, 2000; Khan & Tzortzopoulos, 2016), efficiency (Checkland, 2000) and acceptability (Khan & Tzortzopoulos, 2016; Tzortzopoulos, 2004).

After the focus groups were carried out, the feedback was incorporated into the solution and the final version of the solution was presented. Further details of the evaluation carried out in this research can be found in the next section and the outcome of the evaluation is presented in Chapter 7.

**Table 3-18. Framework for evaluating usefulness and effectiveness of the solution in this thesis**

| CRITERIA | ATTRIBUTES | ATTRIBUTE DEFINITIONS |
|---|---|---|
| Usefulness | Flexibility | Adaptability of the framework to the current practice of tolerance management |
| | | Generalizable to different project sizes and types (e.g. modular construction, timber frame construction) |
| | Practicality | Clarity on the content (e.g. steps, documents, techniques) of the framework |
| | | Ease of the use and simplicity of implementing the framework |
| | Applicability | Appropriateness of the framework, more specifically its content, for the current practice of construction companies |
| Effectiveness | Efficacy | Ability of the framework to achieve the intended output (i.e. preventing tolerance problems at stages preceding the assembly on site) |
| | Efficiency | Whether reasonable resources (i.e., time, cost) are used to achieve the intended output |
| | Acceptability | Ability of the framework to make users believe in its value to practice |

### 3.4.5.1 Overview on the Organisation of the Focus Groups

The first focus group (FG1) took place on campus on 5.11.2018 and started at 13.15 hours. The participants of this focus group consisted of four academics and a PhD researcher. The academics in this focus group have industrial experience and have worked closely with the industry throughout their careers. The second focus group (FG2), also on campus, took place on 1.12.2018 and started at 14:00 hours. The participants of the FG2 were two practitioners working in the company in which the first case was carried out. It is worth mentioning that organising the second focus group took almost one year and initially five practitioners were invited but due to various reasons, two participants could eventually make the meeting.

The participants were invited to the focus group meetings by email. The participants had different backgrounds and were selected based on their expertise and interest in tolerance management and also their availability. The researcher had met the participants of the FG2 during the exploratory empirical studies and had interviewed them before. The participants in both focus groups had diverse roles, therefore creative and diverging discussions could be expected. At the same time, given their experience, they were expected to provide discussions of an in-depth nature. Table 3-19 summarises the information regarding the participants in the focus group meetings.

**Table 3-19. A list of participants and their backgrounds in attendance at the focus group meetings**

| NO. | POSITION | BACKGROUND |
|---|---|---|
| Focus Group One | | |
| 1 | Senior Lecturer | Construction Project Management |
| 2 | Senior Lecturer | Construction Project Management |
| 3 | Senior Lecturer | Quantity Surveying |
| 4 | Lecturer | Architecture |
| 5 | PhD Researcher | Architecture |
| Focus Group Two | | |
| 1 | Senior Design Manager | Design Management and Site Engineering |
| 2 | Senior Quantity Surveyor | Quantity Surveying |

The FG1 lasted for nearly 3 hours and the FG2 lasted for nearly 4 hours. A handout had been printed and given to the participants to help them keep track of the steps in the system during and after the presentation. The handout included a schematic representation of the system as well as a brief of all steps including blank and completed documents, presented in Chapter 6.

Both focus groups comprised of two sessions. The researcher commenced the first session by describing the objectives of the focus group for five minutes which was then followed by presenting the system. The presentation in the FG2 took longer because the participants were stopping the researcher and discussing the content. Once the presentation was over, the participants attended a coffee break. The second session started after the participants reconvened from the break. In this session, the researcher asked questions and then moderated the discussions amongst the participants. The agenda of both focus group meetings is given in Table 3-20.

**Table 3-20. The agendas for the focus group meetings**

| TABLE | TABLE DESCRIPTION |
|---|---|
| Agenda of the Focus Group One | |
| 13:00 | Arrival and refreshments |
| 13:15 | Welcome, introductions and instructions |
| 13:20 | Session one: Presentation by the researcher |
| 14:20 | Coffee break |
| 14:35 | Session two: Questions and discussions |
| 16:00 | Summarising the findings by the researcher and his supervisors |
| 16:15 | Wrap up and adjour |
| Agenda of the Focus Group Two | |
| 13:45 | Arrival and refreshments |
| 14:00 | Welcome, introductions and instructions by the researcher and his supervisors |
| 14:05 | Session one: Presentation by the researcher |
| 16:00 | Coffee break |
| 16:15 | Session two: Questions and discussions |
| 17:45 | Summarising the findings by the researcher and his supervisors |
| 18:00 | Wrap up and adjourn |

During the focus groups, the essential skills of a moderator in a focus group meeting, listed by Tremblay et al. (2010) (explained in Chapter 3), were taken as a model followed by the researcher. The questioning route of the focus groups consisted of thirteen questions, each question representing an attribute. Those attributes have been defined in Chapter 3. The list of questions and their corresponding attributes are given in Table 3-21. The questions are ordered from the general to the more specific. The list of those questions had been given to the participants at the beginning of the second session. This was to give an overview of the questions that would be asked to prevent the participants answering the agenda questions before the prior questions would have been fully addressed. The participants were encouraged to reply to the questions actively, make comments and inquiries, and state their feedback and opinion.

**Table 3-21. Questioning route of the focus groups**

| ATTRIBUTES | CORRESPONDING QUESTIONS |
|---|---|
| Efficacy | Is the system useful in a sense that it will lead to an improved tolerance management in construction (i.e. the prevention of tolerance problems proactively)? |
| Flexibility | Is the system adaptable for steel and concrete framed building construction projects? Is the system generalisable to other types of projects (e.g. timber framed construction, modular construction, etc.). |
| Practicality | In terms of clarity and simplicity, is the system easy to implement? |
| Acceptability | Does the proposed system have the potential to be accepted by practitioners and be used in the industry? |
| Efficiency | Does the time and cost needed to implement the system outweigh the costs saved due to eliminated reworks, delays and poor quality? |
| Applicability | Are the documents and techniques developed in the system applicable for the practice of construction companies? |
| Applicability | Is the underlying logic behind the flow of information (i.e. order of steps) suitable? |
| Flexibility | Does the proposed organisational design in TMS fit with the existing organisational hierarchy of your company and typical organisational hierarchy of construction companies in general? |
| Efficacy | Will Part One of the system lead to the full capture of tolerance requirements/risks? |
| Efficacy | Will Part Two of the system lead to the achievement of tolerance requirements/mitigation of tolerance risks? |
| Efficacy | Will Part Three of the system lead to the improved communication of tolerance information? |
| Efficacy | Will Part Four of the system facilitate the verification of the compliance of the achieved deviations with the specified tolerances? |
| Efficacy | Will Part Five of the syetem lead to continually improving tolerance management by reusing the knowledge gained from previous projects? |

Two methods were used to collect data during the focus group meetings: an audio recording and note taking. The participants were informed in the invitation email that the meeting will be recorded. In the FG1, the author of this thesis was taking notes by himself. In the FG2, a PhD researcher had been invited to act as the observer of the focus group to monitor the moderation and the information exchange between the participants themselves as well as the moderator and the participants. Also, notes were taken intermittently by the invited PhD researcher to record the major points made during discussions. After conducting the focus groups, the recorded meetings were transcribed and, eventually, the transcriptions and notes taken were reviewed a number of times.

The confidentiality of the collected data was explained to the participants at the beginning of the meetings and the consent forms were given to them to be signed. This was to ensure that they were willing to attend the meeting on a voluntary basis and the meeting could be audio recorded.

### *3.4.6 Step Six: Conclusion*

The final step of the research was about analysing and consolidating the contributions of the last version of the artefact from two perspectives, namely, theoretical and practical. The theoretical contributions of the research were evaluated by analysing the connection of the findings with the existing theory. In other words, as van Aken et al. (2012) recommends, in this step, it was investigated what the undertaken research can particularly add to the existing literature. The practical contributions were analysed based on the findings during the focus groups and benefits that the developed solution can bring to the industry. After the full potential of the designed solution was realised, the author stated the research needs in the field of tolerance management, which means new research should begin to solve them.

## 3.5 Summary

In this chapter, the choice of DSR for this research is justified and it is explained why other research methods (traditional sciences, action research, case study) are not appropriate for this particular research. The steps to undertake DSR in the literature are reviewed and the adopted steps for this research (problem definition, awareness of problem, suggestion, development, evaluation and conclusion) are presented. The research tools used for each step are presented in details. Moreover, a framework is developed to evaluate the artefact developed in this research.

# CHAPTER 4: **EMPIRICAL STUDIES**

This chapter presents some of the findings from three cases carried out in this research. The purpose of the empirical studies was generally to understand (a) a typical practice of tolerance management, (b) the best practice of tolerance management, and (c) characteristics of tolerance problems that occur in construction projects. The empirical studies in cases one and two are particularly important to fulfil objective one, which was obtaining a comprehensive understanding of the current practice of tolerance management and tolerance problems. The empirical study in case three was particularly important to suggest and develop the solution. In this chapter, fifteen tolerance problems identified in cases one and two are described. The adverse impacts of identified tolerance issues are described from the financial, time and workflow perspectives. Note that the root causes of the identified tolerance problems are analysed in the next chapter.

## 4.1 Empirical Study One: A Commercial Building

### *4.1.1 Background*

#### 4.1.1.1 Project Overview

A brief introduction to case one was given in Section 3.4.2. In addition to that, the procurement strategy and structural system used in this case are described next. The procurement strategy for case one was Design and Build. First, the project had been awarded to another contractor. That contractor started on site, but soon after the company went into liquidation. The new general contractor was awarded the project and had to react quickly when receiving the tender as the project was now behind schedule due to the change of company. Therefore, it was not possible for the newly appointed general contractor to focus on the details, including tolerances, at that stage. Design and Build contingency was included in the scheme to deal with design development risks and the resolution of defects, such as tolerance-related problems. The general contractor engaged itself with the steel, curtain walling and fin subcontractors immediately after it was let the contract. This was due to the risk of tolerance problems that potentially may occur between the structural steelwork and interfacing components. Given the short time period for the procurement of subcontractors in this project, other subcontractors were not involved until a few weeks before they were needed on site. Some of the subcontractors worked under fixed-price contracts. The general contractor made progress payments as the subcontractors were accomplishing each phase of their work. For example, the partitioning subcontractor and dry liners for the internal walls were paid per metre erected per day.

The structure of case one is a steel framework building with composite steel deck-slabs, curtain walling, glazing and masonry panels, suspended $4^{th}$, $5^{th}$, $5.5^{th}$, $6^{th}$, and $7^{th}$ floors and a roof. All ground floor slabs are reinforced concrete and bear directly onto the ground.

### *4.1.2 Tolerance Management-Related Activities and Documents in Case One*

In this section, the methods and documents used for tolerance coordination, communication of tolerance information, and verification of the achieved deviations with the specified tolerances in case one are presented and shortcomings are examined.

#### 4.1.2.1 Specifications

The specifications to which the researcher had access to were developed by a civil and structural engineering consultant and the client. The specifications comprised of different types of information. A summary of the tolerance-related information found in the specifications of case one is presented in Appendix H.

The specifications of structural steelwork, concrete, masonry, projecting feature-find system, stick curtain walling system, natural stone cladding system, ventilated rainscreen cladding system, and outline specification were critically reviewed. The main shortcomings from the specifications in case one are as follows:

- The tolerance information in the specification is sometimes presented in a wrong section. For example, tolerances for lining base plates should be in the section for 'setting-out tolerances', whereas it is in the section for 'workmanship tolerances';
- Some terms are used in the specifications, as far as it is known, have no commonly known definitions and, in the specification itself, they are not properly defined. For example, no definition could be found for 'rough finish' of concrete surfaces, whereas it has been used in the concrete specification;

- Some reference documents listed in the specification, do not exist at all. For example, as far as it is known, there is no reference document called BS 8180, although users for the tolerances of the superstructure in the concrete specification referred to this reference document. Moreover, some of the listed reference documents in specifications have been superseded with new reference documents. For example, according to the specification for structural steelwork, detailed design for the steelwork should be in accordance with 'BS 5950: Structural use of steelwork in building'. However, this standard has been superseded by 'EN 1993-1-1:2005: Design of steel structures'. The consultant who developed the specifications put a clause in the specification stating that "the contractor shall bring to the attention of the engineer any inconsistencies between the requirements of these Standards and this Generic Specification Section". This implies that the consultant is likely to be aware that some of the reference documents have been replaced with new ones and has added this clause to the specification to avoid the extra work of updating the context of the specification, which is replicated for each project over and over, and to also transfer the risk of any problem to the general contractor;
- Two levels of tolerances for flatness (i.e. Service Regularity 1 and Service Regularity 2) are explained. However, it is not exactly specified which class of tolerance is selected;
- In some cases, the specifications require components to be aligned, vertical, and positioned perfectly, however, they do not allocate tolerances for the components being out of position. For example, walls on concrete suspended slabs should be in parallel as stated in the masonry specification; however, no tolerance for this has been specified;
- In some of the reviewed specifications (i.e. structural steelwork, concrete, masonry, stick curtain walling system), it is explained how components can be assembled/constructed so any tolerance problem can be avoided. For example, in concrete specification, it is stated that "power float should be used for surfaces that require tighter tolerances";
- The method that is used to measure deviations is sometimes specified by referring to a reference document. For example, in the masonry specification, it states that deviations should be measured in accordance with British Standards Institution (1990), which is a lengthy document.

However, it does not precisely explain what the relevant information is in this reference document;

- It will be explained in Section 4.1.3.10 that one of the most costly and time-consuming corrections for a tolerance problem was related to the fins attached to the building envelope. Surprisingly, the main tolerance information could be found in the 'projecting feature – fin system' specification, which stated that "lateral adjustment per floor: ± 10 mm horizontally". In fact, it will be explained in Section 4.1.3.10 that this brief information is wrong;
- Contractors try to transfer tolerance risks to other parties. For example, in the 'natural stone cladding system', the cladding subcontractor makes the general contractor responsible for the size and geometric accuracy of other components (e.g. thickness of slabs, position of support systems) in order to be able to install the cladding system within the specified tolerances;
- Tolerance information in each specification revolves around the component in question and disregards the other components, that is, it is not investigated whether tolerances of adjoining components are compatible.

#### 4.1.2.2 Drawings

Some drawings (e.g. fins, retaining walls, precast slabs, steelwork, and tiles) in case one include tolerance information. Figure 4-8, Figure 4-9, Figure 4-10 and Figure 4-11 show how tolerances are displayed on the drawings. A summary of the tolerance information given in these drawings, the type of the information, and the missing tolerance information is given in Table 4-22.

The review of the architectural and engineering designs contents that architects and engineers typically use chain dimensioning in their drawings without specifying tolerances. Thus, tolerances are specified haphazardly in the local or general notes of the drawings. The local notes point to a specific feature with a leader arrow and general notes are usually located in a corner of the drawings.

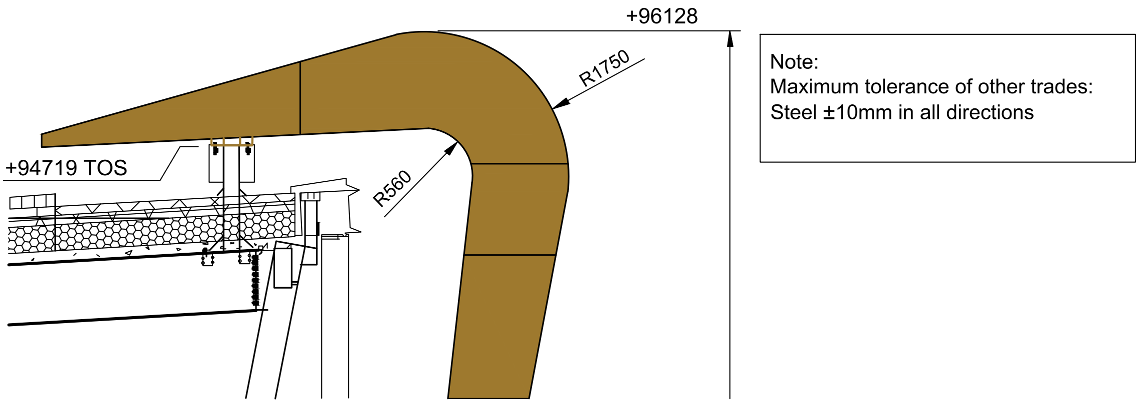



**Figure 4-8. Tolerances displayed on drawings for fins**

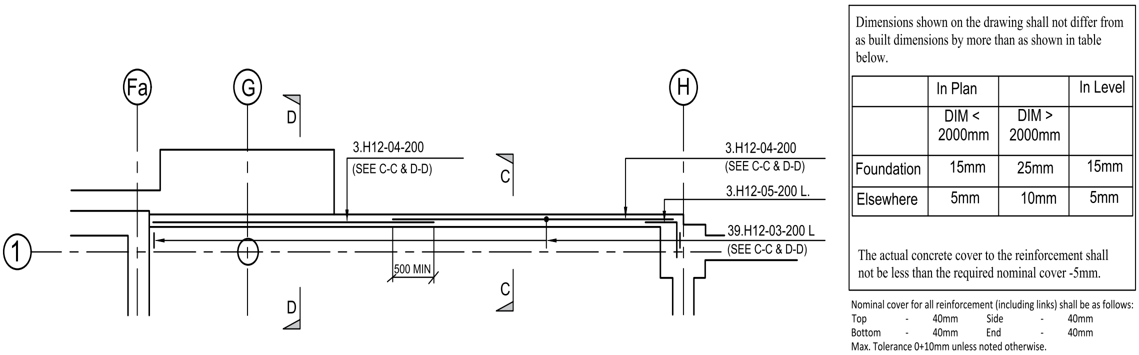



**Figure 4-9. Tolerances displayed on drawings for retaining wall**

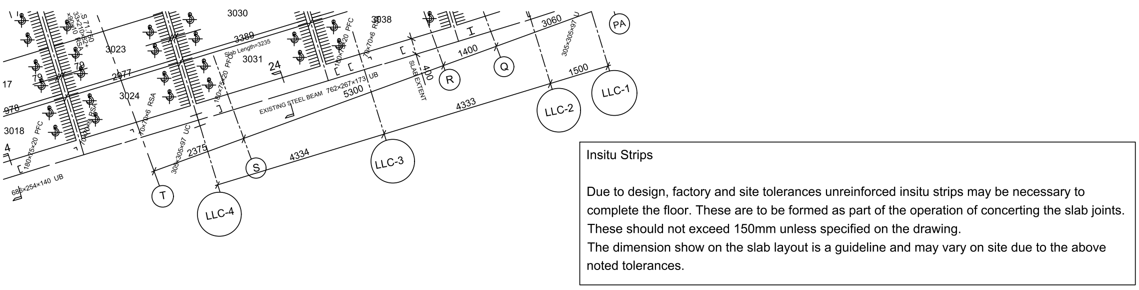



**Figure 4-10. Tolerances displayed on drawings for tiles**

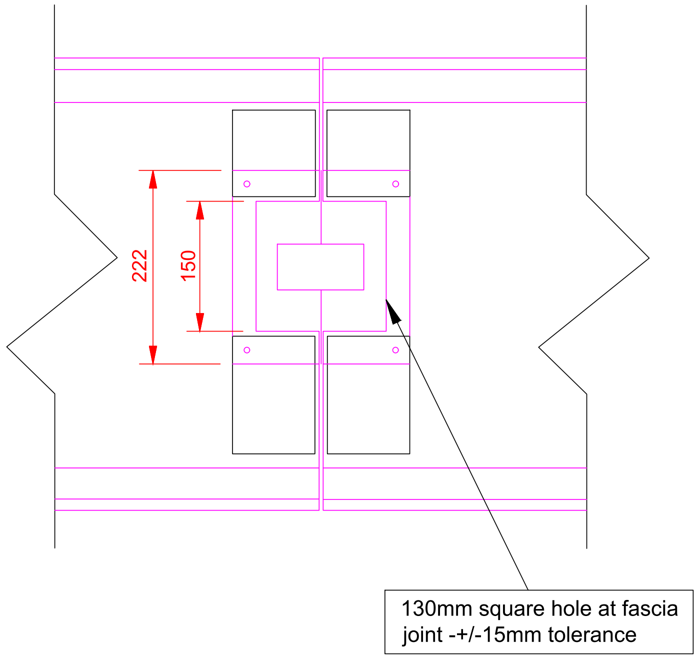



**Figure 4-11. Tolerance displayed on a drawing for the steelwork**

**Table 4-22. Analysis of the given tolerance information in Figures between 4-8 and 4-11**

| FIGURE | TYPE OF THE GIVEN TOLERANCE INFORMATION | DESCRIPTION OF THE GIVEN TOLERANCE INFORMATION | MISSING TOLERANCE INFORMATION |
|---|---|---|---|
| 4-8 | Erection tolerances required from adjoining components to assemble and fit the component in question. | The steel contractor has to erect the columns to be within ±10 mm in all directions. | It is not stated whether the given tolerance is for plumbness or position.<br>There is no tolerance information from the steel subcontractor to check whether the tolerance required by the fin subcontractor is achievable. |
| 4-9 | A generic note describing the permitted deviation between designed and built sizes and levels of concrete works. | Size and level tolerances are given for the concrete work of foundation and other elements. | It has not been specified how the given tolerance information is related to the component shown in the drawing (e.g. whether the component in the drawing is a foundation, whether the dimensions in the components are smaller or larger than 2000 mm). |
| 4-10 | Size tolerances for a set of tiles when put next to each other. | Tolerance for the overall dimensions of the tiles is ±3 mm. | Tolerance for the squareness of the tiles and their joint width has not been specified. |
| 4-11 | Size tolerance for a hole in the steelwork. | Tolerance for the size of a square hole at the fascia is ±15 mm. | Tolerances for the position and form (i.e. squareness) of the hole have not been specified. |

In short, tolerance information in the drawings includes: (a) tolerances for the size or position of the component, (b) tolerances required from the abutting components, (c) overall size tolerances of a set of components when put next to each other, and (d) tolerances for the level of components. It is visible that, although designers have tried to specify tolerances in drawings, the exact tolerance requirement is still ambiguous because tolerance information is not adequately and clearly communicated through drawings.

### 4.1.2.3 Provision for Building Movement

Case one has a complex building structure due to its unusual curvy shape. Also, the data required to anticipate the building movement (e.g. dead load due to the weight of components) was not fully available when designing the structure, due to the way the subcontractors were procured. Hence, in case one, it was not possible to anticipate the exact building movement. The provision for building movement using connections was selected in this project as an approach by which designers could avoid tolerance issues.

Three types of connections were observed in this project to accommodate variations raised by the building movement: expansion connections, sliding connections and adjustable connections.

Expansion connections were used for the concrete slabs and stone cladding to allow for the opening and closing of connections. More specifically, in concrete slabs, expansion connections were used to accommodate movements incurred by temperature and shrinkage effects. The dashed lines in Figure 4-12 show the expansion connections within polished concrete for the roof, and Figure 4-13 shows the expansion connection for the cladding system.

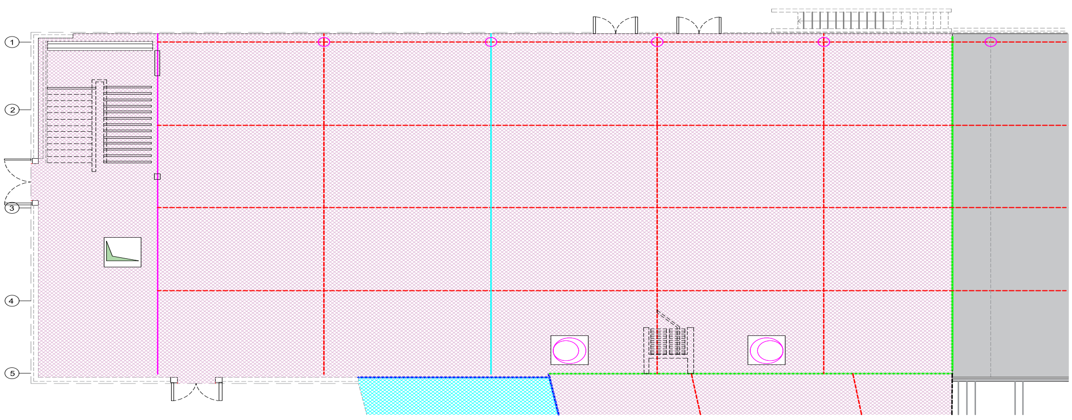


**Figure 4-12. The position of movement connection in the roof**

**Figure 4-13. Expansion connection for stone cladding**

Sliding connections were used for the exterior walling system, stone cladding, and curtain walls to allow for movement. In the exterior walling system, the slotted head track has been provided to allow for the deflection in the primary structural frame. The studs are screw fixed to the slotted head track through pre-formed slots in the track (Figure 4-14). Figure 4-15 shows slotted cladding brackets that absorb perpendicular to the building face. Deviations may be due to the erection, manufacturing, or setting out of building structure or cladding.

The adjustable connection for curtain walls is used which allow deviations of the structural frame to be absorbed (Figure 4-16).

**Figure 4-14. Slotted head track in exterior walling system**

**Figure 4-15. Cladding brackets and their slotted heads**

**Figure 4-16. Adjustable connections for curtain walling**

#### 4.1.2.4 Tolerance Coordination

During the observations and interviews, it was perceived that after designs are developed by subcontractors, they are sent to the Design Manager of the general contractor to be fed into the architectural model. One of the purposes of this process is to ensure that components on site fit together. The key factor determining whether designs fit together is to check whether the tolerances of adjoining components are compatible with each other.

The Design Meetings in case one were held every fortnight. The design team, comprising the architect, engineers and other designers, attended the meetings to develop and integrate designs. These meetings were an important forum for the identification of tolerance risks and finding the resolution for mitigating those risks. In case one, the general contractor recognised the risk with the cladding, fins, and curtain walling. To mitigate such risks, in the first Design Meeting held in July 2015 when the general contractor had just been awarded the project, the general contractor invited the cladding, fin and curtain walling subcontractors along with the architect and the structural engineer to discuss those risks. More specifically, one of the tolerance-related issues discussed during the meeting is that the cladding subcontractor was asked to confirm their load calculation due to the weight of the cladding system to the structural engineer. This was to ensure that the steel frame was able to withstand the loads due to the weight of the cladding system and the final deflection will be within the tolerance.

In short, Design Meetings are an important forum for the general contractor to ensure that the tolerance risks are identified (e.g. the impacts of loadings on the dimensional and geometric accuracy of the structure have been fully anticipated), and measures are taken to achieve tolerance requirements (e.g. the building structure is fully capable of withstanding all loads without any unforeseen deformation). However, in the Design Meetings in case one, the participants could not identify all of the potential tolerance risks and they could not successfully play their preventive role for tolerance problems. This is because:

- During the Design Review Meetings, various issues were discussed. Issues related to tolerances make up a small proportion of the discussions. Moreover, even though those issues (e.g. loadings, deflection, etc.) were discussed on some occasions, their impact on the dimensional and geometric accuracy of the building, and the solutions to mitigate their impact, were lost among many other discussions;
- Regarding the overlap between design and construction, subcontractors often could not be involved in the project until a few weeks before they were needed on site. Hence, it was not often possible to make judicious decisions about tolerance values, tolerance risks, and strategies to mitigate tolerance risks by involving subcontractors whose components were connected tolerance-wise (e.g. adjoining components);
- Even when tolerance risks, and solutions to mitigate them, were being propounded by the subcontractors, in most of the case the general contractor followed the instructions given by the architect and consultants rather than the subcontractors. Nevertheless, the subcontractors work with their components day in/day out and have more knowledge about the risks associated with their components than the other parties. As a consequence, even though tolerance risks in some occasions were identified in the meetings, optimal decisions could not be adopted to mitigate the risks. An example of the impact of this type of tolerance problem, occurring in this case with tolerance problem 8, is explained later.

The aforementioned problems in many occasions made the Design Meetings a forum to reactively remedy the tolerance problems, rather than to proactively prevent them.

### 4.1.2.5 Verification of Tolerance Compliance

According to the interview with the site engineer, he is responsible for verifying the compliance of tolerance requirements in the field. It was observed that in case one the general contractor had their own site engineer and did not necessarily need to rely on surveys from other trades.

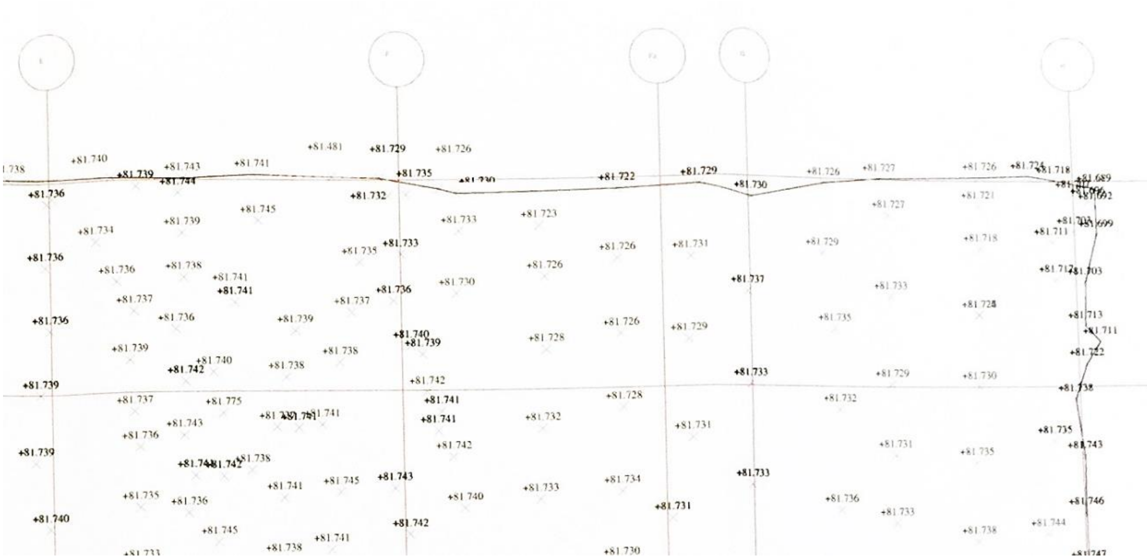


**Figure 4-17. Example of survey results for concrete slabs**

Figure 4-17 illustrates an example of a survey issued by the site engineer. In this survey, the site engineer has used a total station to check whether the flatness of the concrete slabs complies with the specified flatness of the concrete surfaces. In essence, he measured the elevation of several points. However, the site engineer cannot obtain a complete overview of the floor condition using this method. This is because given the time and effort constraints, the site engineer can only measure the elevation of a certain number of points.

### 4.1.2.6 Quality Check Sheets

The researcher was able to review the Quality Check Sheets prepared by the steel subcontractor. In these documents the tolerances of components to be controlled are given. The Quality Check Sheets enable the general contractor to understand the tolerance requirements of the steelwork, and verify the compliance of those requirements before the handover.

Moreover, the general contractor has their own internal Quality Check Sheets. The researcher was able to access a few of them, including the Quality Check Sheets for the formwork, concrete, structural steelwork, cladding, partitions and ceiling. Although present in the concrete Quality Check Sheet, tolerances were not included in any of the other Quality Check Sheets, not even in the one for the steelwork. In the concrete Quality Check Sheet, only the following tolerance-related question was included: "Formwork monitored for line/level and within tolerances?"

### *4.1.3 Identified Tolerance-Related Problems in Case One*

A summary of the identified problems in case study one is given in this section.

#### 4.1.3.1 The Depth of the Concrete Slab (Tolerance Problem 1)

Within the agreement between the general contractor and the concrete contractor, the subcontractor was obligated to achieve the Service Regularity 2 (SR2) and pour 130 mm of concrete over the floors. It was agreed that the concrete was to be poured to a thickness and not to a level, because if the concrete was poured to a level then the metal deck may be overloaded. According to the specifications given by the metal decking subcontractor, the composite floor itself could deflect 5.9 mm as a result of loads before the pouring of the concrete, and it could deflect 28.3 mm after the concrete was poured. The latter being due to the fact that the deck is designed to always be in the elastic range. When concrete is poured using the 'flood' technique, care must be taken that the assumptions made, in respect of the concrete thickness, are reflected in the calculation of the deflections of the slab and the supporting beams. The risk when using this system is that the deflection of the deck under the weight of wet concrete results in a variable depth of concrete (Davison & Owens, 2012). As a result, it is difficult to achieve a perfect level, such as an SR1 or an SR2, when pouring concrete on a metal deck (The Steel Construction Institute, 1997).

The specification stated that the deflection calculation was based on a slab poured to the constant thickness specified. Additional weight, as a result of the deflection of the supporting structure, was not taken into account. However, the general contractor thought that it was possible to pour more concrete to level the concrete slab to a certain extent. In fact, as explained earlier, making the concrete thicker will often overload the metal decking and this may indeed cause more deflection. During a conversation with the general contractor and the structural designer, after the first floor was poured, the general contractor was told that the depth of concrete must be 130 mm and this could not be modified, neither for first floor nor upper floors.

Following the conversation between the general contractor and structural designer, the structural designs were rechecked before pouring the upper floors. The general contractor was told by the structural engineer that it is possible to pour the concrete up to 150 mm to level the concrete surfaces. This still left the general contractor with uncertainty because there was the risk of more deflection of the metal decking. This could have been a major problem, but the general contractor managed to pour the concrete to the correct level without exceeding the 150 mm and the maximum weight of the concrete. The researcher did not have access to the surveys to investigate whether there was an exceeding deflection than was originally specified due to making the slabs thicker.

#### 4.1.3.2 Flatness of Concrete Slabs Affected by Unforeseen Circumstances (Tolerance Problem 2)

The concrete subcontractor worked until 3 o'clock in the morning to achieve the desired finish on the first floor, but was stopped from working after 10 o'clock in the evening when pouring upper floors. This was because residents living in the boats on the canal and guests at a hotel near to the site complained to the Environment Agency of the Local Authority and claimed that noise pollution had occurred. As a result, the concrete subcontractor could not get the finish that was required on those floors (Figure 4-18). Rainfall was another reason why the desired finish was not achieved. In some places there were puddles on the floors. As a result, grinding machines and a layer of epoxy were required to level the floors and make them within tolerances.

**Figure 4-18. Effects of unforeseen circumstances on a slab finish**

Polished concrete was listed as the final finish in the concept design but, as a result of the problems explained above, up to 30 mm of latex was needed in some areas to level the slab, whereas a 3 mm latex layer should normally be used. Moreover, the client agreed that the concrete would not be the final finish and a vinyl sheet was to be put on the top.

#### 4.1.3.3 The Edge of the Concrete Slab and the Cladding Bracket (Tolerance Problem 3)

To maintain the installation tolerances for the stone panels, adequate clearances and the adjustable connection should be detailed for the connection between the stone panels and the steel frame. The connection between the stone panels and the steel frame is one of the most critical connections because of the irregularities of the steel frame. An adjustable bracket was used in this project. The bracket provided approximately a 30 mm horizontal adjustment to accommodate the steel frame and erection variations.

The brackets were attached to the steel beam. At the roof level, the bracket also had a connection with the edge of the concrete slab. The edges of slabs can vary as much as 10 mm according to (CONSTRUCT Concrete Structures Group, 2010). However, in this case, because the bracket was in line with the steel, the concrete slab could not deviate towards the outside, otherwise it would have conflicted with the bracket (Figure 4-19).

**Figure 4-19. Modified edge of the concrete slab**

This problem occurred in the project and the general contractor had to cut the concrete before installing the brackets. The researcher was not able to measure how much the concrete was beyond the steel beam, but he assumes that the concrete slab was within the tolerance as discussions regarding this issue were not observed between the general contractor and the concrete subcontractor.

#### 4.1.3.4 Concrete Slab and Recessed Skirting (Tolerance Problem 4)

There were stud partition walls in the circulation areas which had three layers of plasterboard. At the bottom of the wall, the skirting was recessed and essentially the top head of the plaster board was terminated 100 mm above the floor. The skirting board was effectively creating a flush line all the way through. In this situation, the contractor had to take extra care on the upper floors, which were undulating due to the first and second identified tolerance problems (explained above).

There were a few options to overcome the problems with the floor undulation and the skirting board: the contractor could either set the skirting to the highest point and then use latex, or other compound materials, to smooth out the floor finish, or they could grind the skirting so that the top level is constant but the depth of the skirting changes with the floor.

The contractor’s budget did not allow to feather out any undulations. Therefore, approximately £8,000 was put against the floor finish package as a contingency. This was done on the basis that even though the floor slab was undulating, it could still be within tolerance and meet SR2 finish requirements. The general contractor would have had to spend money to remedy this to achieve the required end product because the subcontractor was not contractually obliged to recover the cost. Figure 4-20 shows the details of skirting board.

In this situation, perhaps the most pragmatic solution was to set the skirting board at the highest point and keep the skirting consistent all the way through. This is because, if the subcontractor scribed the skirting board from the lowest point, the skirting could go up to approximately 20-30 mm. However, if this were the case, the top line would look fine but the bottom of the skirting would be going up and down and it would not be acceptable aesthetically.

This case shows that there was a miscommunication between the general contractor and the subcontractor when the tendering team of the general contractor were pricing the scheme. The subcontractor probably was not fully aware of the details that the general contractor was trying to achieve, and the tolerance requirements were not properly and contractually negotiated with the concrete subcontractor before commencing the concrete work on site. Moreover, this implies that the general contractor had not established an effective process to identify the risks of these problems occurring during the short period of the tender process. Otherwise, more budget and time would have been allocated towards the skirting board detail, and more thought would have been given to the floor finish.

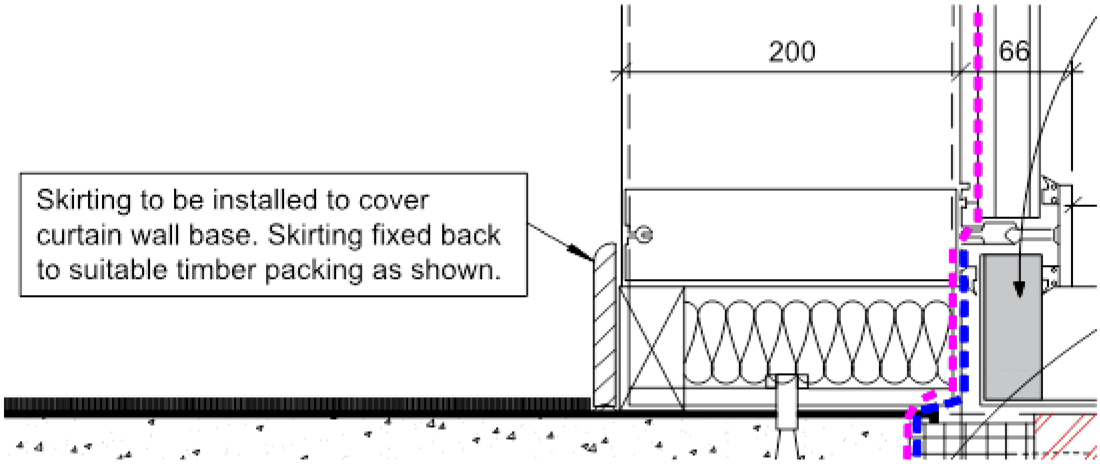



**Figure 4-20. Skirting board details**

### 4.1.3.5 Concrete Slab and Door Frame (Tolerance Problem 5)

The problem with the connection between the concrete slab and the door frame is similar to the problem explained with the concrete slab and door frame. In short, the general contractor may need to either sand the bottom of door frame if it sits on the high point of the slab or, if the slab is lower where the door frame sits, which means the door frame might sit so far off the slab, then the contractor will need to make up with latex to level out the slab. The door and its frame are illustrated in Figure 4-21.

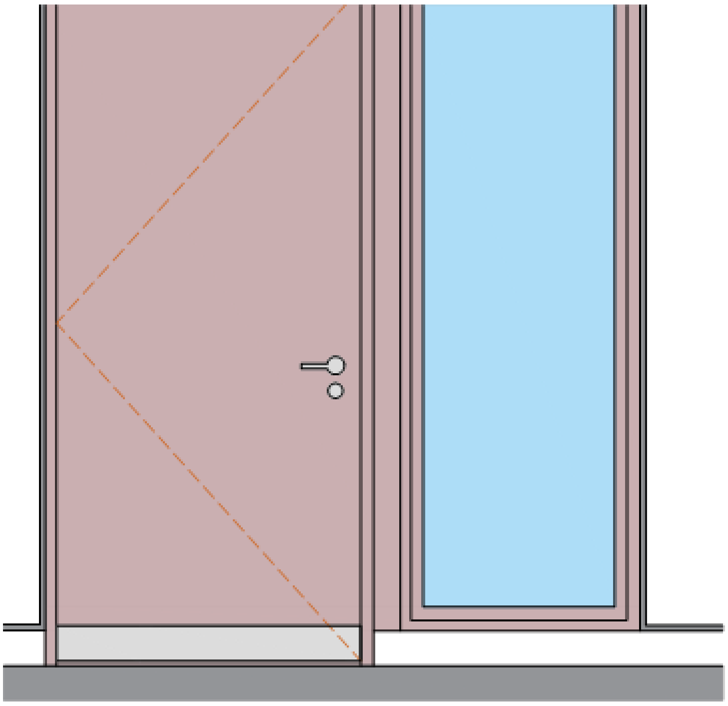


**Figure 4-21. Door frame and its position relative to the concrete surfaces**

#### 4.1.3.6 Concrete Slab and Glazed Balustrading (Tolerance Problem 6)

The problem with the connection between the concrete slab and the glazed balustrading is also similar to the two problems explained above. In this project, the glazed balustrading is running around the atrium at each level. The glazed channel sits much flush with the concrete slabs but because, again, the concrete slabs are undulating, the first alternative to fix this problem is that the balustrading should be put at the highest point, otherwise, it would be slanted. The general contractor also proposed the second alternative that the contractor could weld the channels and make the balustrade flexible in a way that it could move vertically. Hence, there would be no need to use the highest point all the way around and the average point could probably be considered. Eventually, the general contractor selected the first alternative and put the glazed balustrading at the highest point.

#### 4.1.3.7 Plumbness of the Steel Framing Systems Studs (Tolerance Problem 7)

The stone cladding subcontractor used a spirit level to measure the plumbness of the Steel Framing Systems (SFS) studs. It turned out that the SFS studs were slightly out of plumb and they had not been checked for verticality by operatives and, as a result, the cladding subcontractor could not proceed. The general contractor then notified the relevant subcontractor that their work was out of tolerance and that they must correct it. The incurred consequential costs would be recovered from the subcontractor's account, because they had failed to carry out their work to the proper standard. Moreover, the general contractor suffered a delay because of this problem.

#### 4.1.3.8 Steelwork and Cladding in Elevation 4 (Tolerance Problem 8)

The cladding subcontractor had developed a design in which the offset was 460 mm from the grid (or 272 mm from the steel column to the face of the stone panels). This was amended by the architect as there was a need for more room between the cladding and the steelwork to accommodate the installation. The architect commented that the set out should be 480 mm from the grid (or 290 mm from the face of the stone panels). This allowed the cladding system to accommodate only 15 mm deviations raised from the steelwork and cladding. Figure 4-22 shows the drawing developed by the cladding subcontractor and the architect's comments.

Ultimately, the cladding subcontractor was correct and in Elevation 4, the steelwork leant into the building up to 30 mm at the roof level. So, a 15 mm tolerance requested by the architect was not enough for the cladding system.

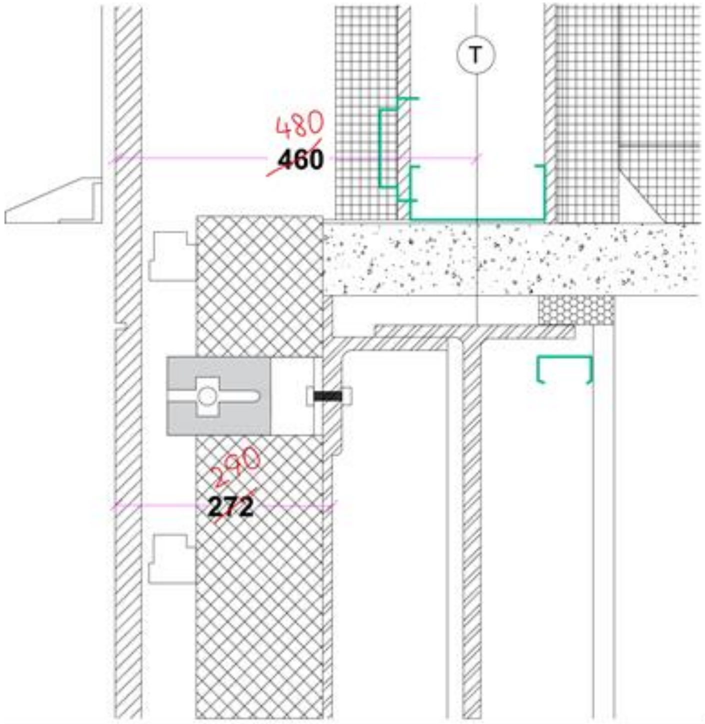



**Figure 4-22. Cladding details in Elevation 4**

In this example, the subcontractor had to remove all the installed stone panels and order new ones, which cost about £10K. Afterwards, the general contractor put in new steel stiffeners and shimmed the steel, which cost about £20K. The shims used varied between 10 mm and 35 mm. In the interim, the subcontractor was unable to proceed with the work for a period of time and the general contractor had to incur this cost. The subcontractor then installed the stone panels. This problem in total created an added cost for the general contractor of £30-40K.

#### 4.1.3.9 Steelwork and Cladding in Elevation 9 (Tolerance Problem 9)

When the cladding subcontractor put the stone panels on and the dead load was applied to the steel frame, the stone panels started to sag. This meant that the cladding did not stay at the correct level and, in general, everything was sinking downwards. It was noticeable that the gap between the channel and the stone panel in some areas were bigger and the gap was not consistent all the way through (Figure 4-23). It was not clear whether it was the angle or the I-beam that was bending. When looking at this issue on site, it seemed more reasonable to conclude that the angle, fixed inside the steelwork, was not strong enough to withstand the cladding’s weight and was bending. The distance between the angle and the stone panel was

420 mm, which exaggerated the problem and caused the angle to bend further. Stone panels would fall off as a result of this problem and cause safety issues, and also the final cladding would not look aesthetically pleasant.

This shows that the steel frame was not stiff enough. The problem could have been avoided by using connections that can accommodate up to 20 mm of building movement. The cladding subcontractor had recommended the movement connections but, in the specification of the stone cladding, the consultant believed that movement connections were not required. Moreover, there was a misunderstanding between the structural engineer, the cladding subcontractor, and the general contractor. The cladding subcontractor warned the other parties in the Design Meeting about the probable vertical movements of the cladding, but a final decision was made not to use movement connections. In that time, it was not anticipated that the steel beam or the angles would twist more than anticipated causing all the stone panels to sag.

Installing connections that could accommodate variations at this stage of the construction required the subcontractor to take off the already installed stone panels and install the appropriate connection. This resulted in an additional cost of £5-7K and it took around 1 month to complete. The cost of installing the appropriate connection at the beginning of the project would have been negligible. The researcher could not find whose responsibility it was to incur the cost of rectifying this problem.

**Figure 4-23. Elevation 9 and sagging stone panels**

### 4.1.3.10 Steelwork and Fins (Tolerance Problem 10)

In the tender process, the structural engineer requested the input from the steel specialist subcontractor into the design for the steelwork. This was misunderstood by the tendering team and the assumption was that the steel frame was sufficient to withstand any loads arising from the fins. When the fin subcontractor was involved in the project, the general contractor realised that they had to bid for a stiffer structural frame to enable the frame to withstand wind loads on the fins and dead loads due to the weight of the fins on the building. The study of wind impact on the fins, initially overlooked, is very complicated. As a result of this, additional steel was introduced into the building. This cost the general contractor around £70-80K. Installing the fins was a very slow process and it delayed the project for two months.

The initial design of the fins allowed the steel columns to have the tolerance of ±10 mm for any points on the steel columns. This tolerance was not achievable given the curvy shape of the building and building movement due to the metal-deck floors but this was discussed just before the installation of fins. The general contractor waited until the steel frame was erected and then surveyed the connection points of the fins. It turned out that the assigned tolerance was too small for the final position of those fins and the connection holes had to be altered.

Where the fins connect, two plates fit together and that connection has 4 bolts to hold the bracket which then supports the fin. There are brackets on each floor. The new design had the brackets with slots. The fin brackets had holes in the steel frame, but the general contractor had to complete the additional work of drilling plates and creating new holes in the existing steel frame.

Therefore, movement joints were provided for the fins which allowed them to move vertically ±15 mm. This means that the fins could go 15 mm up or 15 mm down, and 30 mm overall. The movement joints comprise compressible gaskets that will allow the fins to have a reasonable tolerance for their position. The new design may result in a slightly bigger gap at one side of the fins where the steel column comes through the back of the fin. In simple words, the compressible gaskets act as compriband to take up the deviations of the columns. This is to reduce the chance of the wind whistling through a hole. The shapes of the fins stayed the same. The difference between the new design and the prior design is that in the old drawings the fins had an interface with the columns with fixed connections, whilst in the new design the fins are connected to columns by flexible connections. Figure 4-24 shows details of the fin connections.

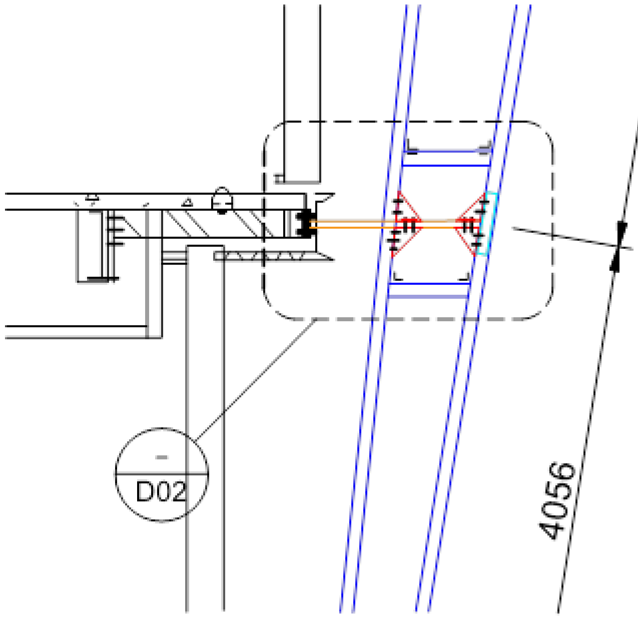



**Figure 4-24. Details of a fin connection**

## 4.2 Empirical Study Two: A Terraced Warehouse / Manufacturing Building

### *4.2.1 Background*

#### 4.2.1.1 Project Overview

As mentioned in Section 3.4.2, case two is a warehouse/manufacturing building that is subdivided into individual units. Offices are accommodated in the first floor, which is a mezzanine floor. The programme was scheduled in a way where the steelwork was erected in five phases. After each phase, the general contractor carried out grouting column base plates prior to the cladding being installed. One week after grouting, the cladding subcontractor started to fix the walls and roof.

The building structure is a twin span portal frame with hipped ends and a central valley beam. The frame spans approximately 26 m. The height to the underside of the haunch is 8 m, with a roof pitch of 6° after dead load deflection. A composite roof sheeting utilising cold rolled purlins and composite wall cladding via proprietary sheeting rails were designed for the building.

### 4.2.2 Tolerance Management-Related Activities in Case Two

In this section, the methods and documents used for managing tolerances in case two are presented and the shortcomings are examined.

#### 4.2.2.1 Specifications

The researcher was able to access two types of specifications in this project: the structural design specification developed by an engineering consultant, and the performance specification developed by a planning and architectural consultant. The specifications comprise different types of information. In the structural design specification, it was stated that the document was to summarise the structural design principles to inform the client, design team, and general contractor for detailed tender purposes. In the performance specification, it is mentioned that the purpose of the document is to comprise information adopted from reference documents which must be taken into account by designers and specialist subcontractors. This information is related to the structure of the building, mechanical systems, electrical systems, and external works. A summary of the tolerance information found in the specifications of case two can be found in Appendix I.

The findings from the specifications in case two are similar to the findings in case one. The only further finding is that in the structural design specification, a risk register is presented to assist the general contractor in terms of assessing the amount of contingency to be applied (Table 4-23). One of the identified risks is related to the dimensional tolerance risk for the cladding system. It has been stated that it is the responsibility of the general contractor to ensure that the cladding system can accommodate the movement and deviations of the steel structure.

**Table 4-23. Identified tolerance-related risk in the performance specification**

| ELEMENT | RISK | MITIGATION |
|---|---|---|
| Cladding Interface Deflection Criteria | Cracking of brickwork / finishes | The deflection criteria assumes flexible cladding. The building frame has been designed to the deflection criteria specified. It is the responsibility of the main contractor to ensure that the cladding system procured can accommodate the specified movements and tolerances. Any change to the criteria specified in this Design Statement to more onerous criteria specified by the cladding subcontractor will have a significant effect on the structural design. |

#### 4.2.2.2 Connections to Accommodate Variations

Two types of connections have been used in this project, namely: expansion connections and butt connections. Expansion connections have been used for the internal concrete slabs and the external pavement. Dashed lines in Figure 4-25 show the expansion connections within the pavement outside the building.

Butt connections have been used for the interior concrete slabs (Figure 4-26). With these types of connections, the slabs are separated with a special prefabricated system. This system aims at transferring the vertical loads between adjacent slabs and minimises the vertical displacement of the slabs due to traffic of machineries on them when the warehouse is in operation.

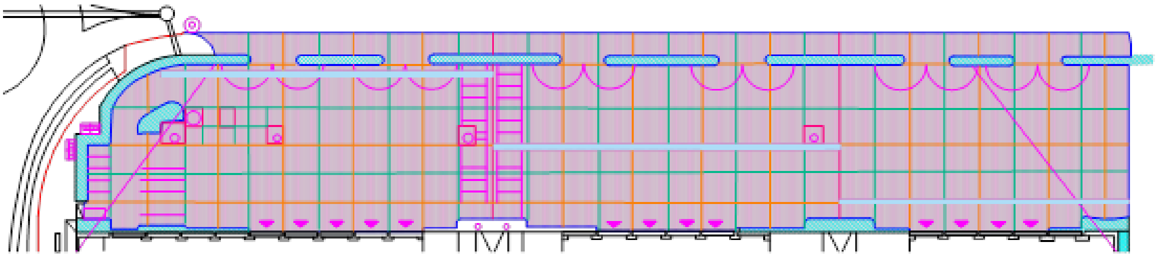


**Figure 4-25. Position of expansion connections in the pavement**

**Figure 4-26. Butt connections for the interior concrete slabs**

#### 4.2.2.3 Tolerance Coordination

Design Meetings were held on a weekly basis. The general contractor had separate meetings with the concrete subcontractor, steel subcontractor and cladding subcontractor. In these meetings, subcontractors could express their concerns about design constraints and pose any questions to the other attendees. However, tolerance conflicts in this project could not be proactively identified. In fact, those meetings were only a forum to find solutions for the incurred tolerance problems and resolve disputes over them. The reasons why the Design Meetings in this case were not effective for tolerance coordination are similar to the reasons stated in case one stated in Section 4.1.2.4.

#### 4.2.2.4 Verification of Tolerance Compliance and Modification of Tolerance Problems

The concrete subcontractor in this project had their own site engineer and did not rely on the surveys of the engineers from the other trades. Nevertheless, as part of the contract with the steel subcontractor, the general contractor was responsible for checking the steelwork. Hence, the general contractor made a request for an external engineer to come to the site and survey the steelwork after the completion of each phase of the work.

The site engineer, in his visits to the site, inspected the location of base plates, the elevation of the bottom of columns, and the elevation of the top of columns. Figure 4-27 shows an example of his surveys for the steelwork. However, neither the site engineer nor the general contractor controlled the position of the beams, purlins, and ties on the roof, and there was not even a visual inspection of those members.

After the completion of the inspections, the external site engineer produced a report summarising all the information relating to the plumbness of the columns and the location of the base plates. When there was a concern regarding the deviation of the structural steelwork, he provided technical advice to the general contractor. The advice included how the steel subcontractor could modify structural members which were out of tolerance and make them within the limits, or at least make them function as intended.

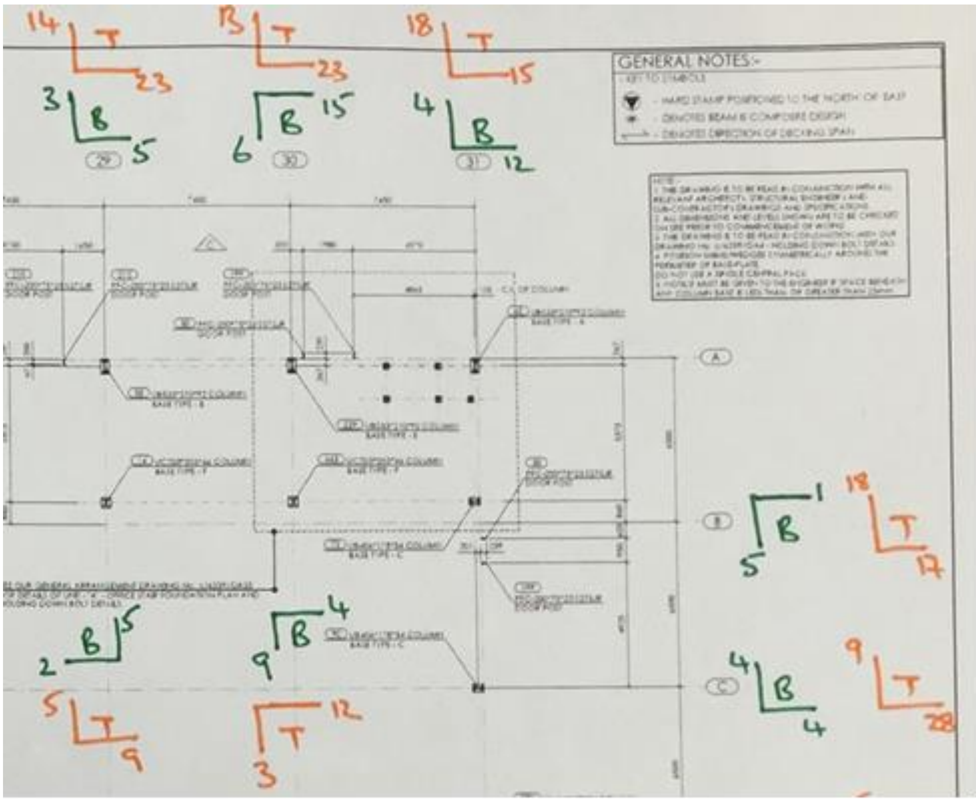



**Figure 4-27. An example of a survey for the structural steelwork in case study two**

In the survey shown in Figure 4-27, B stands for 'Bottom' and T stands for 'Top'. The direction of the arrows shows the direction in which the columns should be moved, and the number next to the arrow shows exactly by how much the column should be moved. For instance, consider the column in Gridline 31A, the direction of the arrow at the top is to the right and the number next to it is 15. This means that the top of the column is 15 mm out of plumb towards the left and it should be moved 15 mm to the right to be exactly in the correct position.

The process of the plumbing and levelling of the steelwork was decided via an interaction between the steel subcontractor and the site engineer (Figure 4-28). The site engineer first inspected the plumbness of columns using a total station and then one of the steel erectors moved the columns using a hammer, Mobile Elevating Work Platforms (MEWPs), or proprietary pulling devices (Figure 4-29). The steel erector then used wedges to fix the columns in the correct position (Figure 4-30). When the plumbness and position deviations of the columns were within the limits, or were accepted by the general contractor, the steel erectors completed the final bolt tightening.

**Figure 4-28. The interaction between the site engineer and the steel erector to plumb and level the columns**

**Figure 4-29. Moving the columns using a hammer**

**Figure 4-30. Wedging the column to fix it after being plumbed and levelled**

### *4.2.3 Identified Tolerance-Related Problems in Case Two*

Five tolerance problems were identified during the empirical studies.

#### 4.2.3.1 Structural Steelwork and Doorway (Tolerance Problem 1)

The site engineer, as explained earlier, controls the plumbness of the columns before the steel subcontractor hands each phase of their job over. Apart from the regulations for the plumbness of columns, according to British Constructional Steelwork Association (2010), clause 9.6.8.4, perimeter column alignment, the location (Δ) of the outer face of a perimeter column at base level relative to the line joining the faces of adjacent columns can be 10 mm. However, the site engineer was not concerned about whether the columns were aligned, although he checked the position of the base plates for reporting them to the general contractor.

**Figure 4-31. Location of the site engineer when measuring the misalignment of doorways**

In doorways, in addition to tolerances for plumbness of each individual column, the rows of columns, parallel flange channels (PFCs), and cladding rails must fall within the specified limits to be able to fit the doorframes between the PFCs without any adjustment. The site engineer first set the total station outside the building and started to control the cladding rails and stanchions (Figure 4-31). The results of the survey are given in Table 4-24.

**Table 4-24. The survey results of the doorways in case two**

| THE DOORWAY | SURVEY RESULTS |
|---|---|
| The doorway between Gridline 6 and 7 | It was 18 mm twisted, because the cladding rail attached to the column in Gridline 6 was 16 mm towards north, and the cladding rail attached to the column in Gridline 7 was 2 mm towards south. |
| The doorway between Gridline 7 and 8 | It was 7 mm twisted, because the cladding rail attached to the column in Gridline 7 was 3 mm out of position towards north, and the cladding rail attached to the column in Gridline 8 was 4 mm out of position towards south. |
| The doorway between Gridline 8 and 9 | It was 9 mm twisted, because the cladding rail attached to column 8 was in the correct position, without being twisted, but the cladding rail attached to the column in Gridline 9 was 9 mm off towards north. |
| The doorway between Gridline 9 and 10 | It was 9 mm twisted, because the cladding rail attached to the column in Gridline 9 was 6 mm out of position towards north, and the cladding rail attached to the column in Gridline 10 was 3 mm out of position towards south. |
| The doorway between Gridline 10 and 11 | It was only 2 mm twisted, because one end of the cladding rail attached to the column in Gridline 10 was 12 mm out of position towards south, and the cladding rail attached to the column in Gridline 11 was 10 mm out of position towards south. |
| The doorway between Gridline 11 and 12 | It was the most consistent one. |

The doorway between Gridline 6 and 7 was the least consistent, with 18 mm of twist. The general contractor and the site engineer argued that this problem was incurred because either the steels that support the bottom of PFC at the two sides of the columns were slightly bent or the columns were twisted at their base plates. They believed that the location of the columns was not the cause of this defect as the columns had been lined up properly.

The site engineer, two staff from the general contractor's team, and three staff from the Steel Subcontractor's team were involved in solving this problem (Figure 4-32). The site engineer and the general contractor decided that using a string line was the best way to make the doorways aligned. This was because if both cladding rails in a doorway were towards north or south, they were still straight and could be accepted. The agreement between the engineer and the general contractor was to make the doorways consistent in a way that they would not be twisted more than 5 mm.

**Figure 4-32. Staff involved to solve the problem with doorways**

The initial idea was to first pull the string line between Gridline 6 and 11 all the way through to understand how much the cladding rails were out of position, make the cladding rails and stanchions behind them as consistent as possible by moving the columns, and then wedge in the columns (Figure 4-33). To do this, the supervisor of the steel erectors was asked to help the engineer and shift the columns if necessary (Figure 4-34).

**Figure 4-33. Use of the string to control the alignment of doorways**

**Figure 4-34. Steel erector adjusts the column using a hammer**

After starting to move the columns, it transpired that there was another problem: when they were trying to get one end of a cladding rail aligned, the other side was moving, i.e. after getting one side within tolerance, the other side would be out of tolerance. For instance, the cladding rail between Gridline 9 and 10, attached to column 9, had to be shifted 6 mm, but when it was pushed 6 mm in, the other side was then being pushed 6 mm out. The site engineer had to bear in mind that, in fact, he was dealing with two doors. This was due to the flexibility of the cladding rails and PFCs, as they were not fixed to the ground. So, the site engineer had to make a balance between the two sides of a column.

In the doorway between Gridlines 10 and 11, the cladding rails attached to columns in Gridline 10 and 11 were in a good position and the site engineer did not have to rectify them. In the doorway between Gridlines 9 and 10, the site engineer was only able to move the column in Gridline 9 and the cladding rails attached to it, so the doorway between Gridline 10 and 11 was not impacted. The site engineer then decided to move the whole unit in Gridline 9. Thus, the steel erector loosened the bolts in the base plate and pulled the whole system, including the column, two PFCs, and the cladding line, towards south (Figure 4-35).

**Figure 4-35. Bolts are loosened at the front to adjust the columns in the desired orientation**

After using the string line, moving/rotating the columns and then wedging them in, the site engineer once again used his survey instrument to make sure that the columns, the cladding rails, and PFCs were aligned. To do so, he had to set the right-hand end of the cladding rail in Gridline 10 as the baseline which he named Ref A. Then he measured the location of the cladding rails and the stanchions behind them between Gridline 6 and 11 in relation to Ref A. The result was that the doorways were almost consistent, except the doorway between Gridline 6 and 7 which was 11 mm twisted, but he was unable do anything more to correct this problem.

The general contractor was also concerned that pouring the concrete against the columns and PFCs may push them backwards and make them out of alignment again. Hence, the general contractor consulted with the concrete subcontractor and, to mitigate this risk, the concrete subcontractor backfilled the outer side of the columns before pouring the concrete (Figure 4-36).

**Figure 4-36. Backfilled outer side of the steelwork with gravel to avoid movement due to pouring concrete**

#### 4.2.3.2 Wavy Purlins (Tolerance Problem 2)

As a modern industrial building, the roof slope in case two is quite low compared to conventional industrial buildings. Purlins with Z sections were selected for this project by the designer of the cladding subcontractor. Such purlins are often used for buildings with roof slope of 10° to 15° (The Steel Construction Institute, 1997), which means it was not appropriate for this project due to the shallow slope of the roof. Instead, purlins with C sections are more suitable for shallow roofs (The Steel Construction Institute, 1997). Figure 4-37 shows how the purlins are installed on the roof.

**Figure 4-37. Installed purlins on the roof**

In case two, the purlins have been designed with sag rods. Figure 4-38 shows the details used to fix the rods to the purlins. The use of rods prevents the purlins from twisting during erection and stabilises the lower flange against wind uplift (The Steel Construction Institute, 1997). The sag rods were fitted between the bottom hole to the top hole of the adjacent purlin going down the roof slope.

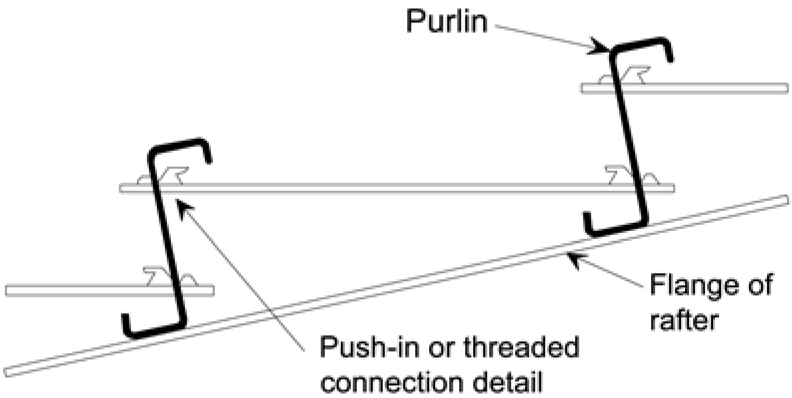



**Figure 4-38. Purlins with sag rods**
**(adopted from The Steel Construction Institute, 1997)**

In this case, there was an argument between the steel and cladding subcontractors. The purlins on the roof which support the roof panels were not straight and in the correct positions (Figure 4-39). As a result, the cladding subcontractor was concerned that there would be no fixing points for their panel. The cladding subcontractor also argued that this problem has occurred in previous phases of the steelwork as well.

The cladding trade emphasised that if the steel subcontractor did not fix the problem, resulting in them having to overstretch the roof cladding system to overcome this defect, then this would eventually result in leaks in the building. In such a case, the cladding subcontractor would be responsible for taking the remedial actions and spending the time and money on fixing the problem. This is because the steel subcontractor by that time would have already left the project and it would not be possible to prove that this problem was a result of their mistake. The general contractor supported the cladding subcontractor's argument and accepted the problem with the first three purlins next to the gutter.

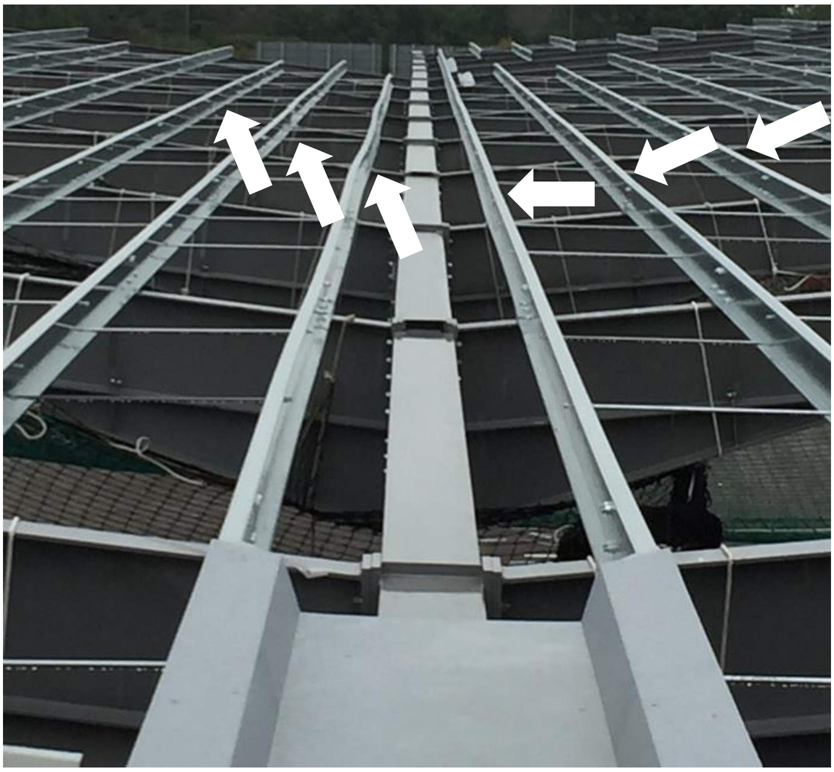


**Figure 4-39. Wavy purlins on the roof**

The steel erector argued that struts are produced in a factory and they naturally have slight deviations from being completely straight. When those deviations are accumulated over the roof, it can result in the purlins being about 20 mm out of straightness. The steel subcontractor eventually decided to order a new threaded bar. They decided to take the struts out and lock in new threaded bars which had the same function as the struts. They planned to put a nut in the side of the purlins and fix them from the top, not the bottom. This allowed for tighter tolerances in their work.

The cladding subcontractor believed that due to the problem with the purlins and ties, they were lacking positioning joints for their panel. This is because of some low spots and high spots on the ridge. They emphasised that the work must be modified before the handover. The cladding subcontractor argued that they were the only trade who always had to solve the problems with the steelwork. They had experienced the same problem in phase one of the steelwork and the problem was recurring. The cladding subcontractor requested to sort the defect and added that it should not recur in the next phases of the steelwork.

Eventually, after the steel erectors held a short meeting, they decided to bring down the purlins and ties (Figure 4-40). They concluded that the ties were not long enough and they were pulling the purlins back too much. The steel subcontractor replaced the ties and the problem was resolved.

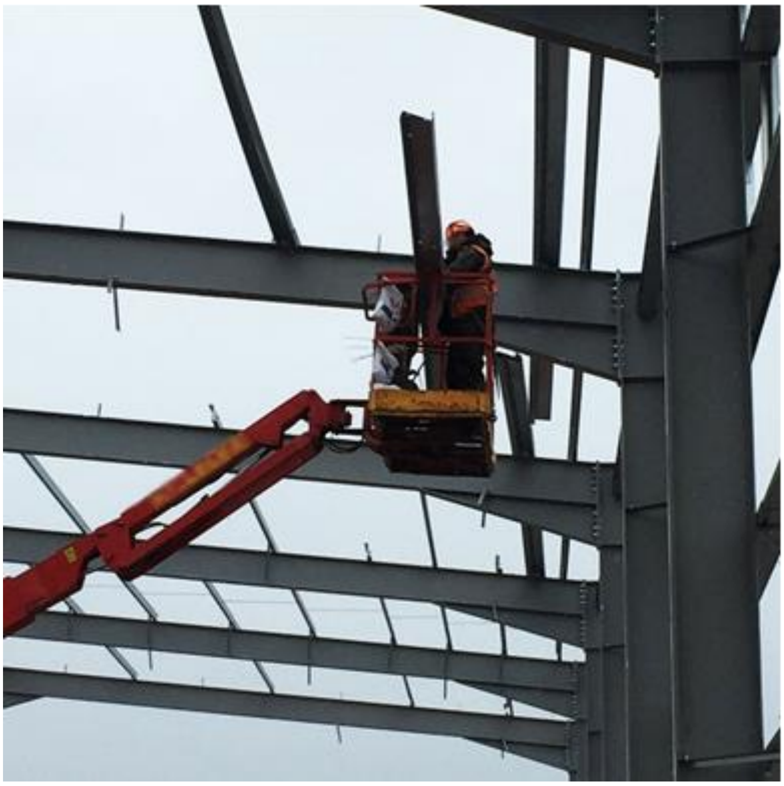


**Figure 4-40. Removing the purlins from the roof**

#### 4.2.3.3 Lack of fit in the steelwork (Tolerance Problem 3)

The starting point of the steelwork was from Gridline 1. The building was erected from Gridline 1 towards Gridline 31. The crane was inside the building to erect the steelwork up to Gridline 30. Figure 4-41 shows the positions of the crane when lifting the rafter in Gridline 28.

**Figure 4-41. The crane inside the building up to Gridline 30**

To erect Gridline 31 and complete the structure, it was initially planned to build a crane platform outside the building using concrete. The steel subcontractor and the general contractor initially decided to build the crane platform between the warehouse and the road next to it. Figure 4-42 shows the position of the crane as initially planned.

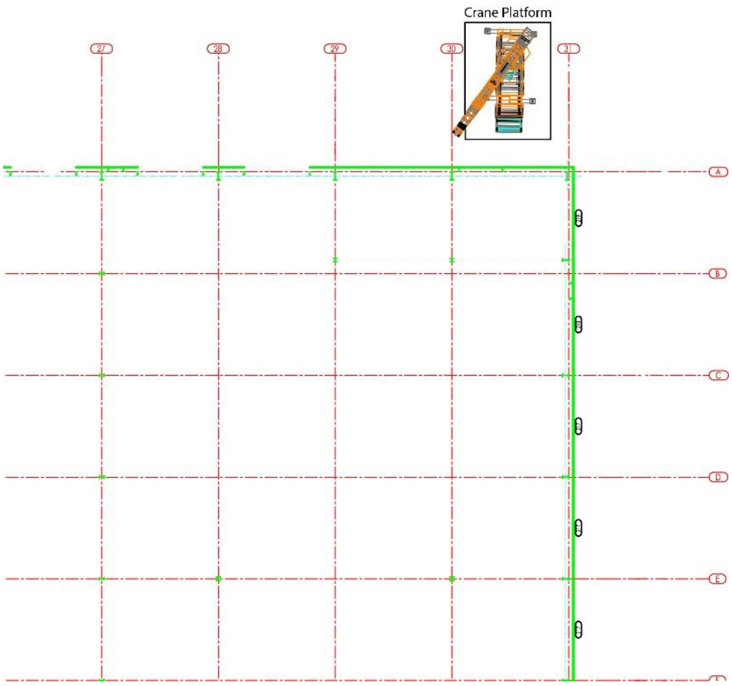



**Figure 4-42. The initial plan of the crane platform to erect the second side of the building**

After a meeting was held between the steel subcontractor and the general contractor, it was decided they would pull the same crane outside of the building instead of building the crane platform. The crane was then placed at the end side of the building, which was being used as a parking space for staff. Figure 4-43 shows the position of the crane.

**Figure 4-43. The position of the crane to erect the second side of the building**

Pulling the crane to the parking space meant that the building had been constructed in two sides and then the steel subcontractor had to connect the beams of those two sides (i.e. connect the two sides of the building together). Figure 4-44 depicts the location of the two sides of the building.

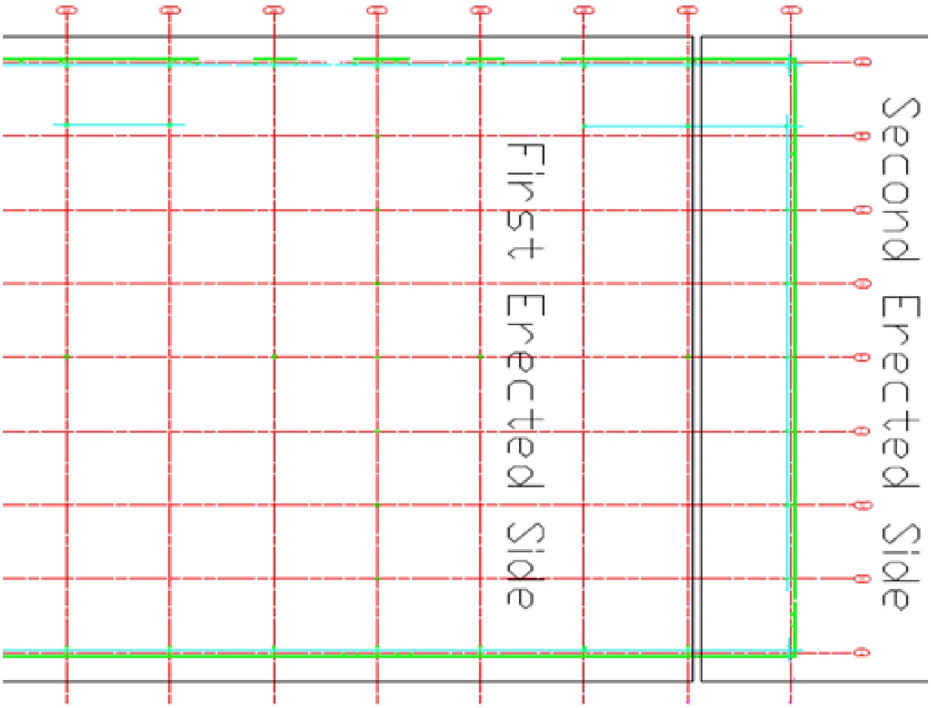



**Figure 4-44. The two sides of the building and the place where they are connected**

The contractor conclude that all of the columns in Gridline 31, except column A and J, were out of plumb from the general contractor's point of view. Having a closer look, even columns A and J were out of plumb according to the British Constructional Steelwork Association (2010). As explained earlier, the accepted inclination of columns, according to British Constructional Steelwork Association (2010), could be 11 mm. Columns B, C, D, E, and F were especially out of plumb of up to nearly four times more than the permitted value for inclination. Hence, the steel subcontractor had to pull both faces of the building (the first erected side and the second erected side) to the outside of the building using a crane and other machines and equipment.

Table 4-25 summarises the survey results after the completion of the modification process, including the direction that the columns were oriented and the amount of deviation in each direction. For example, according to Table 4-25, the bottom of the column positioned in the Gridline 31B after erection is oriented 3 mm towards north and 5 mm towards west. The top of the column is oriented 34 mm towards south and 18 mm towards east. Hence, the inclination of the column in 31B is 37 mm towards south and 5 mm towards east. In Table 4-25, Table 4-26 and Table 4-27, 'Inc.' refers to the inclination, 'N' means north, 'S' means south, 'W' means west, and 'E' means east. The red colour in the columns shows those that are out of the tolerance for plumbness and should not be accepted.

**Table 4-25. Results of the first survey for Gridline 31 after the erection was**

| COLUMN | FIRST SURVEY AFTER ERECTION | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | BOTTOM (MM) | | | | TOP (MM) | | | | INCLINATION N/S | INCLINATION E/W |
| | N | S | E | W | N | S | E | W | | |
| 31 A | | 12 | 4 | | | 26 | 18 | | 14 S | 14 E |
| 31 B | 3 | | | 5 | | 34 | 18 | | 37 S | 13 E |
| 31 C | | 6 | 4 | | | 41 | 9 | | 35 S | 5 E |
| 31 D | | 8 | 17 | | | 44 | 15 | | 36 S | 2 E |
| 31 E | 11 | | 2 | | | 21 | 17 | | 32 S | 15 E |
| 31 F | 16 | | | 6 | | 24 | 10 | | 40 S | 16 E |
| 31 G | | 6 | | 7 | | 25 | 10 | | 19 S | 17 E |
| 31 H | | 1 | 1 | | | 21 | 4 | | 20 S | 3 E |
| 31 J | | 3 | | | | 7 | | 5 | 4 S | 5 W |

Figure 4-45 shows the nominal position of the columns, the deviation of the columns, and the orientation in which the columns are deviating. Moreover, the arrows next to the columns represent the amount of deviation of the columns in each orientation. Thus, to rectify the columns and to pull them into their nominal position and orientation, they should be moved towards the opposite orientation of their inclination by the same amount of the deviation. Figure 4-46 is similar to what the site engineer produces after each survey. The site engineer in this project indicated the survey results manually on drawings but other engineers may produce electronic versions of survey results.

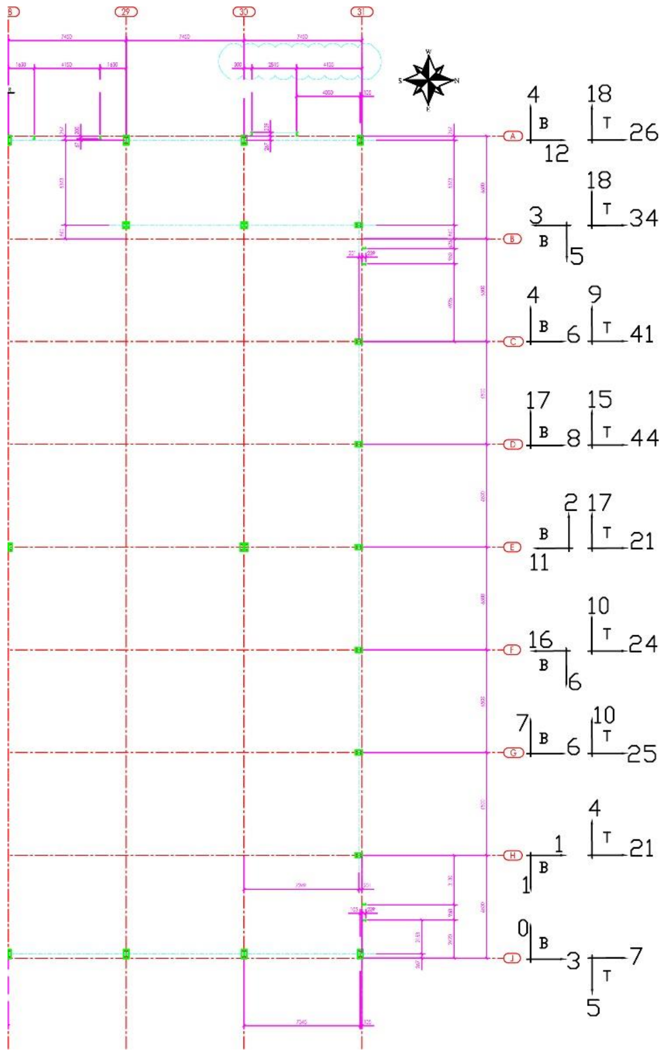



**Figure 4-45. Survey results for columns in Gridline 32**

Table 4-26 summarises the survey results after the structure was erected between Gridlines 25 and 31. More specifically, Table 4-26 shows the deviation and orientation of the columns in those Gridlines. Figure 4-45 illustrates by exactly how much the columns should be pulled and in what direction. The difference between Table 4-26 and Figure 4-45 is that Table 4-26 shows the deviation, orientation, and inclination of the columns on site, while Figure 4-45 shows the orientation to which the columns should be moved to ensure that they are in the exact position with no inclination.

**Table 4-26. Results of the first survey between Gridlines 25 and 30 after the erection was completed**

| COLUMN | FIRST SURVEY AFTER ERECTION | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | BOTTOM (MM) | | | | TOP (MM) | | | | INC. N/S | INC. E/W |
| | N | S | E | W | N | S | E | W | | |
| 25 A | | 6 | 6 | | | 18 | 19 | | 12 S | 13 E |
| 26 A | | 8 | 5 | | | 19 | 11 | | 11 S | 6 E |
| 27 A | 1 | | | 3 | | 23 | 2 | | 22 S | 1 W |
| 28 A | | 4 | | | | 21 | 11 | | 27 S | 11 E |
| 29 A | | 5 | 3 | | | 23 | 14 | | 18 S | 11 E |
| 30 A | | 15 | | 6 | | 23 | 13 | | 8 S | 7 E |
| 29 B | 2 | | 5 | | | 9 | 5 | | 7 S | |
| 30 B | | 4 | | 9 | | 12 | | 3 | 8 S | 6 W |
| 26 E | 3 | | 2 | | | 21 | 15 | | 18 S | 13 E |
| 28 E | 4 | | 8 | | | 15 | 19 | | 11 S | 11 E |
| 30 E | | 8 | | 4 | | 25 | 24 | | 17 S | 20 E |
| 25 J | | 8 | 8 | | | 13 | 7 | | 5 S | 1 E |
| 26 J | | 2 | 5 | | | 15 | 1 | | 13 S | 4 E |
| 27 J | | 2 | | 7 | | 17 | | 8 | 15 S | 1 W |
| 28 J | 1 | | 1 | | | 22 | | 4 | 21 S | 3 W |
| 29 J | 3 | | | 8 | | 13 | | | 10 S | 8 W |
| 30 J | | 4 | | 4 | | 9 | 4 | | 5 S | 8 E |

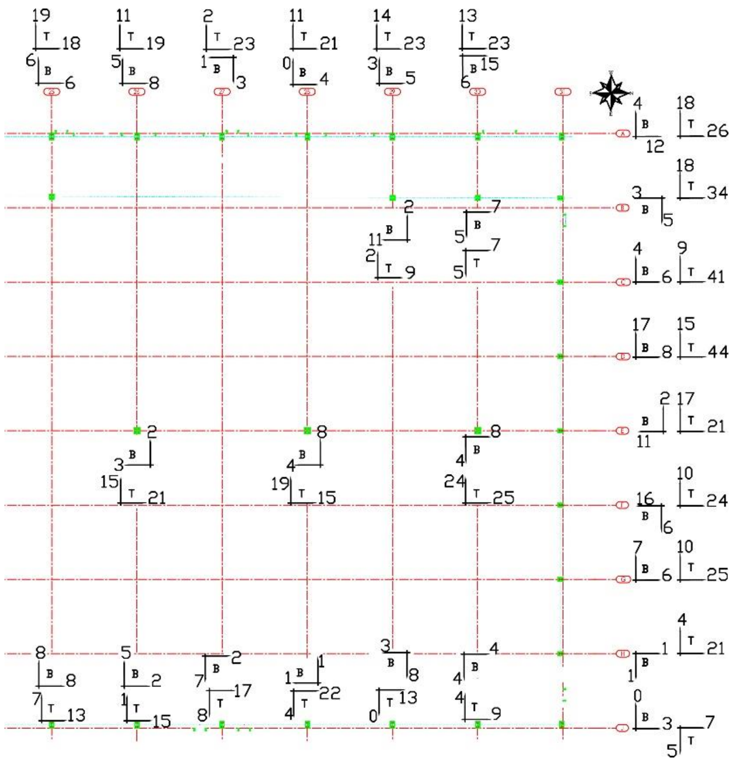


**Figure 4-46. Survey results made by the site engineer between Gridlines 25 and 31**

According to Figure 4-46 and Table 4-26, the first erected side of the building is leaning towards the Gridline 1. Similarly, the second erected side of the building is lying back exactly towards the same direction (i.e. towards the Gridline 1). As a result, the beam across the top between Gridlines 28E and 30E from the initial side has an overlap in Gridline 30E where the two sides of the building are connected.

In fact, a closer inspection reveals that two separate buildings were built as part of the structure for this project and they must be eventually connected to form the final structure. Figure 4-47 shows how the steel erector was trying to fit the problematic beam in the Gridline 30E. One end of the indicated beam was free-floating and there was no space for it to fit at the connection.

**Figure 4-47. The beam between the Gridlines 28E and 30E had an overlap in Gridline 30E**

To overcome this challenge, both sides had to be pulled towards north which meant they were pulled outwards. The steel erector tried different ways to move the structure. One of the attempts involved loosening two bolts of the column base plate in Gridline 31C. Afterwards, the steel erector started to pull the column using a forklift truck towards north (outside of the building) as the column was 35 mm out of plumb towards south (Figure 4-48).

**Figure 4-48. A forklift truck was used to pull the second erected side of the building towards north**

After the steel subcontractor used a crane and a forklift truck in various ways to move the columns and frames, it seemed that the second erected side could not be pulled further. The steel subcontractor then began to use a portable manual hoist along with maxiflex wire rope (Figure 4-49).

**Figure 4-49. A portable manual hoist along with maxiflex wire rope being used to pull the steel frame to an acceptable position and orientation**

One of the major problems during the process of adjustment and alignment of the columns was that when the steel erector tried to have one column right and plumb, the other columns were being pulled. In other words, the steel subcontractor was actually making the other columns out of plumb when rectifying an individual column. The steel subcontractor once decided to move the columns regardless of the tolerances in order to first ensure that the beam was fitted. However, the engineer of the general contractor refused to accept this idea because the structure could result in being remarkably out of tolerance.

Table 4-27 shows the results from the final survey between Gridlines 25 and 31. The inclination of columns 27A, 28A, 29A, 30A, 30A, 31B, and 31C in a north and south direction are not acceptable according to the agreed inclination limit of 15 mm. Considering the British Constructional Steelwork Association (2010), Column 25A should be added to the list of errors as any inclination more than 11 mm is not acceptable. In the east and west directions, column 30A is oriented 19 mm towards east which is not acceptable.

Moreover, Table 4-27 demonstrates the changes made in the orientation and inclination of the columns between Gridlines 27 and 31. Figure 4-50 demonstrates the final survey results and the changes made in the orientation and inclination of all the columns. Overall, it can be induced from Table 4-27 that the whole building is leaning towards south and east. The red colour in columns shows those that are out of the tolerance for plumbness.

**Table 4-27. Changes made in the orientation and inclination of the columns between Gridlines 25 and 31**

| COLUMN | FINAL SURVEY AFTER ERECTION | | | | | | | | | | CHANGES MADE | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | BOTTOM (MM) | | | | TOP (MM) | | | | INC. N/S | INC. E/W | BOTTOM (MM) | | | | TOP (MM) | | | | INCLINATION N/S | INCLINATION E/W |
| | N | S | E | W | N | S | E | W | | | N | S | E | W | N | S | E | W | | |
| 27 A | 1 | | | 3 | | 23 | 2 | | 24 S | 5 W | | | | | | | 21 | | | 4 |
| 28 A | | 5 | | | | 21 | 11 | | 16 S | 11 E | | 1 | | | | | 10 | | 11 | |
| 29 A | | 5 | 3 | | | 23 | 14 | | 18 S | 11 E | | | | | | | 9 | | | |
| 30 A | | 15 | | 6 | | 23 | 13 | | 18 S | 19 E | | | | | | | 10 | | 10 | 12 |
| 31 A | | 12 | 4 | | | 15 | 18 | | 3 S | 14 E | | | | | | 11 | 8 | | 11 | |
| 29 B | 2 | | 5 | | | 9 | 5 | | 11 S | | | | | | | | 4 | | 4 | |
| 30 B | | 4 | | 9 | | 12 | | 3 | 8 S | 6 W | | | | | | | 12 | | | |
| 31 B | | 1 | | 5 | | 17 | 18 | | 16 S | 13 E | 3 | 1 | | | | 17 | 16 | | 21 | 10 |
| 31 C | | 4 | 4 | | | 28 | 9 | | 24 S | 5 E | | 2 | | | | 13 | 32 | | 11 | |

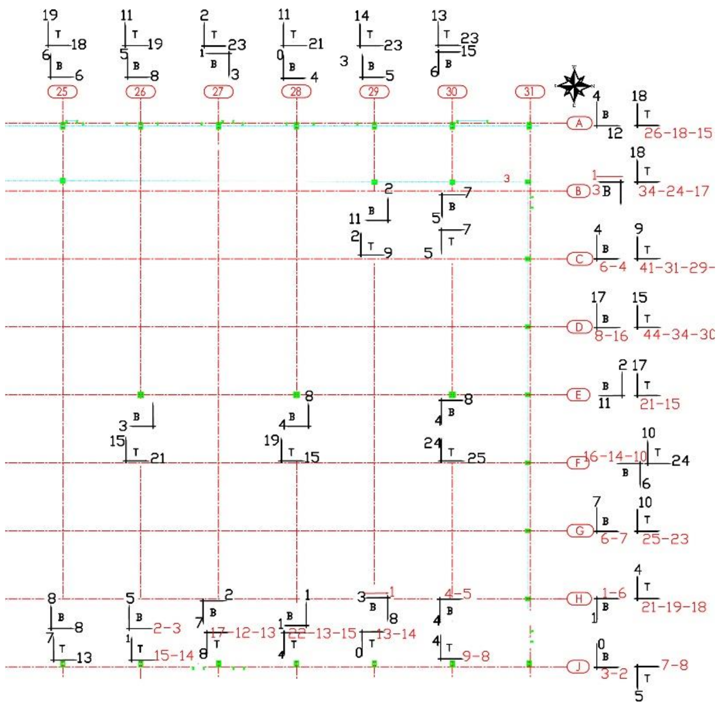


**Figure 4-50. Survey results and the changes between the Gridlines 25 and 31**

Eventually, after one day of moving the steel, trying different solutions, utilising various equipment, and involving: (a) all staff from the steel subcontractor, (b) an external engineer, (c) the senior engineer of the general contractor, (d) the envelope package manager working for the general contractor, and (e) the project manager of the general contractor, it transpired that the beam could not be fitted.

Consequently, the steel subcontractor trimmed the beam to be able to make the connection fit. Figure 4-51 shows the moment when the steel erector was shortening the beam. Moreover, the second erected side of the building was still considerably out of tolerance and the last row of the columns was oriented towards the inside of the building (south).

**Figure 4-51. The steel erector trimmed the beam**

Given the fact that the building will be used for commercial purposes, there was a risk, although small, that the functionality of the building would be affected due to the incurred orientation of the steelwork. In addition, because the columns are out of plumb, the structural integrity of the building in the long term may be adversely affected. The other potential risk was that the cladder could not install the envelope, but this was not observed by the researcher. Above all, the steel subcontractor trimmed the beam to fit it at the interface. As far as the researcher is aware, the beam was cut in an ad hoc way and permission from the structural designer was not acquired. Note that any change in structural members may adversely impact upon the stresses and load paths and is not recommended (Curtin, Shaw, Parkinson, Golding, & Seward, 2008).

In summary, the steel subcontractor ended up with an accumulation of tolerances towards the end of the portal and it was out of tolerance at the end. This required a full day's rework to rectify the problem, whereby the steel subcontractor had to move the steelwork and try to position the steelwork back into line.

#### 4.2.3.4 Lack of Fit for Personnel Doors (Tolerance Problem 4)

The doorframes for personnel doors were not plumb and square. As a result, the personnel doors, all except one of them, were squeezing and could not be fitted in square. Even if the doors could be squeezed, they could not be shut and opened properly. The same problem occurred for all high level windows and they were badly pitched. Figure 4-52 depicts the drawing for one of the personnel doors. The galvanised plate of flashing, herein called galv, above the door frame has been marked.

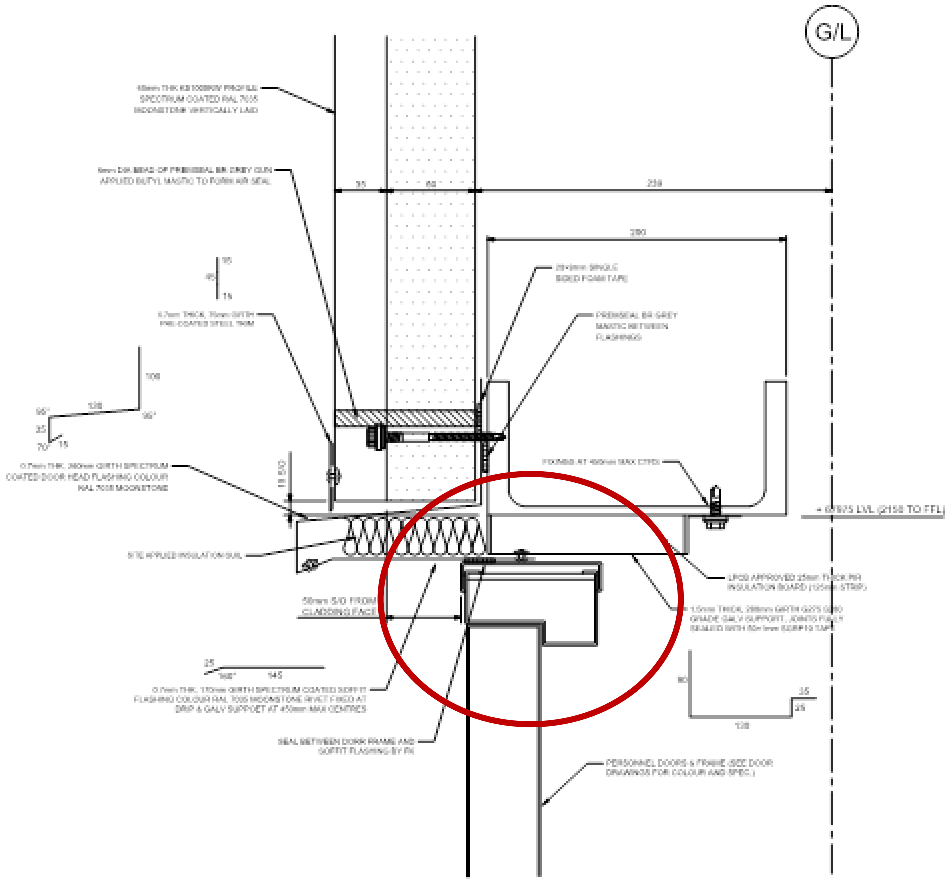



**Figure 4-52. Detail of a personnel door**

The door subcontractor realised this problem when fitting the doors, but by this time it was too late to ask the steel subcontractor to make them plumb as they had already left the site. Even if they were available, it would have been difficult to rectify the error at that stage as the entire structure had been already erected.

To correct this problem, the cladding subcontractor removed the sole installation and the galv. The galv was at both sides of the door frame and window frame. The problem was then solved because having taken off the installation and galv, there was a 24 mm gap from the top of the doorframe and 10 mm gap at each side. However, the cladding subcontractor had to again flash the doors and windows and there were still gaps at the top and the middle. Figure 4-53 shows the gaps around one of the personnel doors.

**Figure 4-53. The personnel door and gaps around the doorframe**

According to two crew members of the cladding subcontractor, the described problem is relatively common. In the case two, after the construction was started on site, the general contractor determined that 15 mm of column deviation would be permitted. However, when the galv is installed in the door/window frame, the connection between the door and galv does not allow any more deviation. In other words, there is no way to accommodate the deviation of columns in such connections. If the column inclines, which it often does (according to interviewees and observations in case two), the door/window will be out of plumb to as much as the deviation of the column because no jointing techniques have been provided to absorb the deviations.

Before the cladding subcontractor started to install the flashing, the site engineer controlled the plumbness of columns. However, the engineer did not control the plumbness of the posts for the personnel doors which affect the squareness of the personnel doors. Then, when the cladding subcontractor started to install the doors, they relied on the site engineer's measurements, and did not take the squareness of doorframe into account but just started to install the flashing.

After the cladding subcontractor pitched the flashing, the door subcontractor controlled the posts and flashings before starting his job. The door subcontractor measured the distances between the posts from two or three points: bottom, middle and top. The door subcontractor trusted these measurements and concluded that the doorframes were square and doors could be fitted into them.

The researcher used a laser meter to double check the measurements of the door subcontractor. The laser meter showed the same distance of 2.81 m from three points along the door frame. However, this did not necessarily prove that the doorframe was square and the jambs were level. In this situation, two conditions may apply:

- The distances between the two posts are the same and the doorframe is square;
- The distances between the two posts are the same but the doorframe is oriented to either the left or right side.

There was a dispute between the cladding subcontractor and the door subcontractor due to this problem. The cladding subcontractor had sub-contracted the door trade. The cladding subcontractor had handed over the steel opening with installed galv and the door subcontractor then tried to fit the doors/windows to them. The cladding subcontractor blamed the door subcontractor for not correctly checking whether the doorframes complied with the requirements. However, the door subcontractor blamed the cladding subcontractor for not handing over the doorframes and galvs plumb and square. The researcher is not aware how the dispute was resolved, if at all.

### 4.2.3.5 Parallel Flange Channels (PFC) and Abutting Components (Tolerance Problem 5)

When the cladding subcontractors were putting the flashing on top of the PFC, it became apparent that there was a tolerance-related problem. Figure 4-54 shows how the flashing interacted with the bottom of the cladding rail, struts, steel, and bolts.

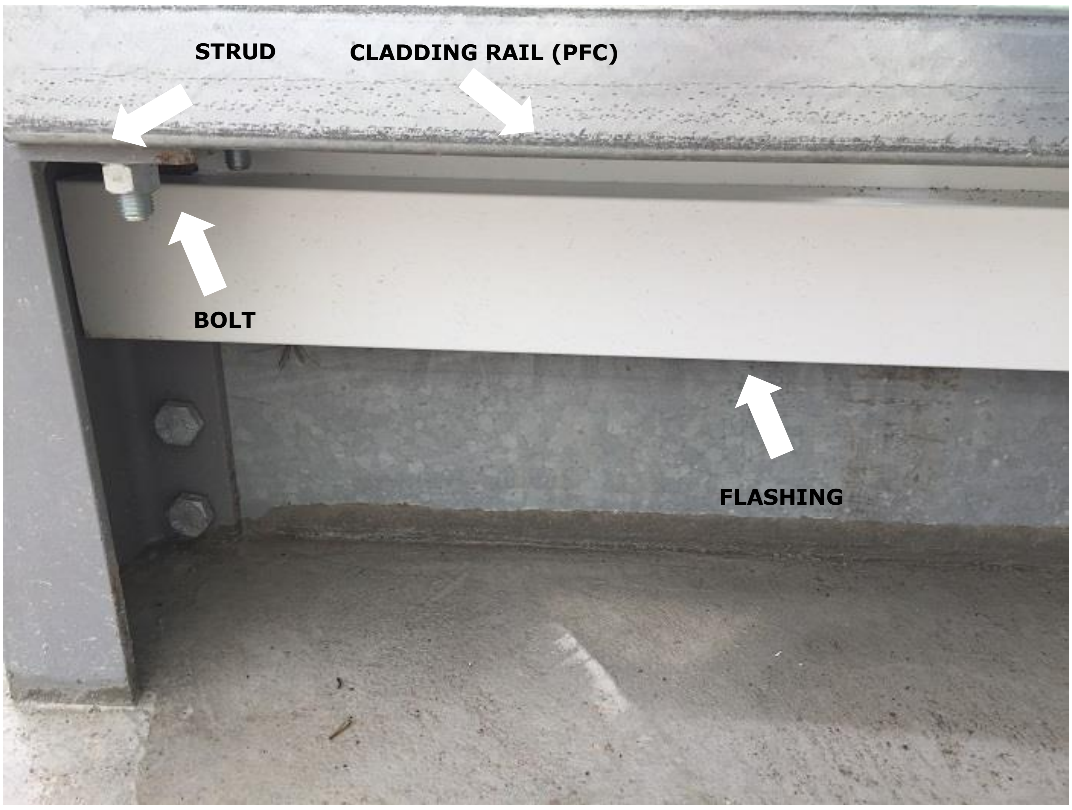



**Figure 4-54. Position of the cladding rails and its abutting components**

Figure 4-54 shows the position of the cladding rail, flashing, and steel from above. The flashing sits on the PFC, it then laps in underneath the first cladding rail and the bolts hold the little vertical struts into the bottom cladding rail.

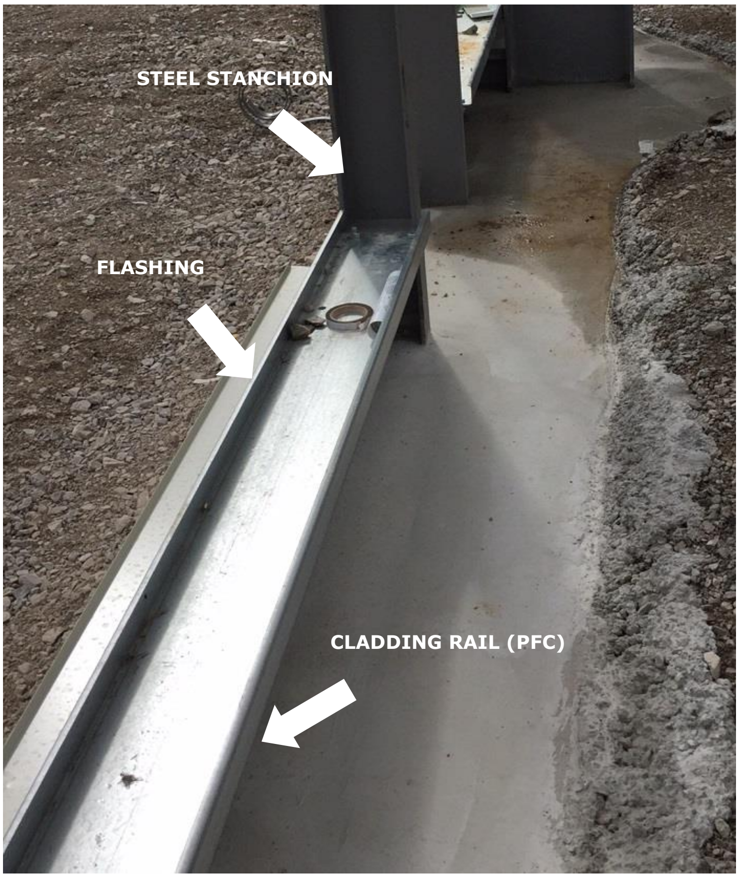



**Figure 4-55. Position of the cladding rail and its abutting component**

The cladding trade had a challenge because the bolts protrude out of the bottom and the trade were sometimes getting a clash with their flashing, which is a rectangular piece of insulation. The cladding subcontractor had to wedge in his flashing. To solve this problem, the cladder span the first bolt around and then put the thread up. Hence, they could reduce what was protruding out underneath and kept the flashing in place.

Having a closer look at this issue, the researcher concluded that the combined deviation of the involved components and its impact on the required clearance between flashing and cladding rail had been overlooked in the connection. This resulted in not having sufficient space to spin the bolts and put threads up. In other words, the tolerance of the steel might have been taken into account by the designer but the tolerance of the other components, which were the PFC, strut, and bolts, had not been considered. Therefore, there was not enough clearance between the flashing and the cladding rail so on occasions there was a clash between the bolts and flashing. Moreover, the researcher observed that there were drawings for the above flashings (and flashing on the roof), but they did not contain details for the flashing and its interface with other components at the bottom.

## 4.3 Cross-case analysis between Empirical Study One and Empirical Study Two

The cross-case analysis between case one and case two is presented in this section. The purpose of such analysis is to identify the similarities and differences in terms of the tolerance-related activities performed in those cases, and the identified tolerance problems. The outcomes of the cross-case analysis also serve to briefly demonstrate the insight gained during these two empirical studies.

Specifications are the main means to communicate tolerance information in both cases. The reviewed specifications constitute a list of several reference documents while many of them are not relevant to the project, or basically are either superseded by other reference documents or do not exist at all. In other words, tolerance information irrelevant to the project can be found in the specifications. The focus of the specifications is only on the component in question and it is not taken into account whether required tolerances are compatible with adjoining components. When developing specifications, a contractor transfers the potential tolerance risks by making other contractors responsible to ensure the tolerance compatibility of adjoining components. In other words, it is not clear whose responsibility is to make sure tolerance requirements will be obtained when components are connected. Another finding in both cases is that specifications are sometimes vague and generic in a sense that they do not exactly specify what the requirement is but rather refer to lengthy reference documents. The terminology to describe tolerance information is not consistent across the reviewed specifications. Overall, one may argue that more effective specifications are required for tolerance management. Moreover, unlike case one, the specification for the structural design of case two includes a risk register in which tolerance risks have been indicated. This seems an effective approach to identify tolerance risks.

Unlike case two, drawings are used as a means to communicate tolerance information in case one. The reviewed drawings have been developed by different designers. Similar to specifications, drawings only revolve around one component and disregard the adjoining components. Tolerance information in general notes is sometimes irrelevant, which implies that the information has been replicated from other similar drawings in other projects. Overall, it is evident that, the tolerance information is still not adequately communicated through drawings. This is, in the author's opinion, due to the lack of an effective and widely accepted tolerancing system. In other words, given there is a lack of an effective and standardised tolerancing system, it is ambiguous what, and how, tolerance information should be presented in the drawings by designers.

Various connections (e.g. expansion, sliding, adjustable, butt) are used in both cases to accommodate variations. Each of those connections are used for a particular source of variation. It was observed that the lack of provision of an appropriate connection in case one (i.e. the problem with steelwork anc cladding in Elevation 9) can result in a significant costly and time-consuming rework. This contents the importance of design of appropriate connects in tolerance management.

Design Review Meetings are a forum in which tolerance issues may be discussed. However, such meetings are generally not effective for tolerance management. The reason is that (a) designers and construction trades whose components are connected tolerance-wise may not be involved in the project when it is needed to be make judicious decisions; (b) the input of participants who work with their components regularly may not be appreciated and the instruction given by designers may be taken into account only; (c) tolerance issues may be lost among many other discussions in those meetings. Overall, Design Review Meetings are reactive to find a solution for occurred tolerance problem rather than proactive to identify tolerance risks and requirements.

In both cases, the compliance to tolerance requirements was verified by the site engineer. Given the time and effort constraints, the site engineers were not able to a give a holistic overview of the accuracy of all components and assemblies. During the observations, it was evident that they may not be even aware of what needs to be measured.

Quality Check Sheets are given by some subcontractors. These enable the general contractor to control the final work of the subcontractors before the handover. However, in both cases, it appeared that only the Quality Check Sheet for the steelwork included considerable information regarding tolerance requirements. It was observed that the site engineer was normally deciding what needs to be measured as no instruction exist. As a result, tolerance problems occurred when the verification of tolerance compliance is not performed before the handover a component (e.g. the problem with plumbness of sthe steel framing systems studs, the problem with wavy purlines).

When reviewing the identified tolerance problems, it is evident that building movement is a reason for occurrence of most of tolerance problems in case one. This shows the importance of building movement in tolerance management. In case two, other sources of variations predominantly caused tolerance problems. Moreover, most of the identified tolerance problems in both cases occurred in the connection between the structure, and cladding and internal partitions. This indicates that tolerance problems are more likely in those areas.

It is evident that tolerance problems can become a matter of dispute (e.g. the problem with wavy purlins), can cause a significant delay (e.g. the problem with steelwork and fins) and fixing them can be very labourious (e.g. the problem with the lack of fit in the steelwork) and costly (e.g. the problem with the steelwork and cladding in Elevation 9). One may argue that given the experience of construction trades, they do recognise the tolerance risks (e.g. wavy purlins on the roof, excessive deflection of concrete slabs) but those tolerance problems are still recurring, and according to interviewees in both cases, those tolerance problems are common.

## 4.4 Empirical Study Three: An Engineering Consultancy

As mentioned in Section 3.4.4, the third empirical study was carried out in an engineering consultancy. The consultancy is specialised in the built environment for several years and provides services for civil and structural engineering, infrastructure, and environmental engineering. What distinguishes this empirical study from the prior two studies is the emphasis of this consultancy on tolerance management, especially at the design stage whereas the tolerance management mechanism in the first two cases were mostly focused at the site level. In fact, the consultancy is known for conducting a relatively advanced practice of tolerance management.

### *4.4.1 Tolerance Management Mechanism Practiced by the Consultancy*

The tolerance management mechanism in this case is explained through a set of steps that are not necessarily performed in order.

#### 4.4.1.1 Step One: Performing Serviceability Analysis during the Structural Design

According to the interviewees in case three (see their details in Section 3.4.4), the consultant designs the structure and then performs the strength and serviceability analysis. The strength analysis is about whether a structural member fails under the Dead Loads, Superimposed Dead Loads (SDL), Live Loads and Lateral Loads. The serviceability analysis includes:

- An examination of whether the horizontal and vertical deflections of the structural members are within permissible deviations when subjected to loads; and;
- An examination of the impact of the deflections on connections between the structural frame and other components (e.g. cladding).

In the context of tolerance management, the serviceability analysis for perimeter beams is of prime importance because their deflection is usually higher than the deflection of slabs, as stated by the interviewees. After the strength check is performed to ensure that the structure does not fail when subject to loads, the serviceability analysis is performed to determine whether the deflection is within the limits and to examine the impact of the deflection on the connections between the structural frame and other components. This is because the weight of the cladding typically applies to the perimeter beam.

#### 4.4.1.2 Step Two: Selecting the Class of Tolerances

It was stated during the interviews that the consultancy determines what class of tolerance should be selected based on the client's outline specification and the type of building. The class of tolerance is also written in the Tolerance and Deflections report. For example, in an office construction project, the height from floor to ceiling was recognised as critical by the consultancy. Hence, the particular class of tolerance was applied to this dimension and the worst-case tolerance analysis method was used to account for the deviations affecting the floor-to-ceiling height. This is because the client needed to ensure that as the dimensions of the area and volume in the offices were achieved as much as possible in order to maximise their return on investment.

#### 4.4.1.3 Step Three: Identifying Tolerance Requirements/Risks

The consultant attempts to identify tolerance requirements/risks early at the design stage and to communicate them amongst designers and construction trades. Two common examples of tolerance requirements given during the interviews were as follows:

- In a warehouse, extraordinarily flat floors are required to ensure the proper function of materials-handling vehicles and robotics. Hence, the flatness of the floors is a key tolerance requirement in a warehouse;
- In any type of building, deviations in floor-to-floor heights are accumulated. This accumulation of deviations may require the client to deploy additional cladding, producing extra costs. Hence, the floor-to-floor height may require stringent tolerances, especially in tall buildings.

Tolerance problems often arise where: (a) the building envelope is attached to the structural frame, (b) internal components are fixed to the building structure, and (c) the internal area of the building is critical and must be bound within stringent limits. Moreover, generally if more restrictive tolerances are specified (e.g. for the building movement) than what can be obtained on site, tolerance problems are likely to occur.

#### 4.4.1.4 Step Four: Collectively Finding Realistic Deflection Limits

The interviewees pointed out that the consultant discusses with the involved parties what level of geometric accuracy can realistically be achieved and whether limits in the reference documents are realistic. For example, according to (CONSTRUCT Concrete Structures Group, 2010), the maximum total deflection of the typical residential concrete slab after the installation of non-structural elements (i.e. partitions and cladding) should be limited to the lesser of Span/500 and limited to a maximum of 20 mm. The consultant and the concrete subcontractor decide collectively whether those limits are realistic and achievable. If the consultant lacks input information from contractors because those contractors have not yet been procured for the project, the analyses (e.g. to determine deflection criteria) are performed based on the limits presented in the existing reference documents and on knowledge gained from previously completed projects. The findings from the analyses should eventually be confirmed by the specialist contractors.

#### 4.4.1.5 Step Five: Selecting Load Sequences

The consultant accounts for the effect of load sequence on the geometric accuracy of the building structure. During the serviceability design, the assembly process should be agreed between the structural engineers and contractor. In the Tolerance and Deflections report, it is explained that the load categories are applied at different times during the assembly process and after the building is handed over. The various stages of load application explained in this document are as follows:

- Once the structure is erected, the dead load derived from the self-weight of the structure is applied to slabs and beams;
- Cladding installation usually occurs once the structure has been completed and before internal fit-out. The weight of the cladding is categorised as superimposed dead load;
- Next comes the stage when the finishes on the floors and ceilings (e.g. services, suspended ceilings and raised floors, mechanical pipes, etc.) are installed. The weight of finishes also makes up the superimposed dead load;
- Lastly, the loads derived from the occupancy of the building, known as imposed loads, are applied.

In the Tolerance and Deflections and Structural Design specification reports of one of the projects, it is discussed that the deflection of the floor slabs and beams should be considered at each stage of the load sequence. The load sequence and the associated deflections for a typical horizontal concrete element are illustrated in Figure 4-56. The symbols used in Figure 4-56 are as follows:

- $\delta_{DL}$: Edge-beam deflection due to self-weight;
- $\delta_{SIDL}$: Edge-beam deflection due to superimposed dead load (i.e. weight of the cladding and finishes);
- $\delta_{IMP}$: Edge-beam deflection due to the imposed load (i.e. occupancy of the building);
- $\delta_{TOT}$: Total deflection of the edge beam.

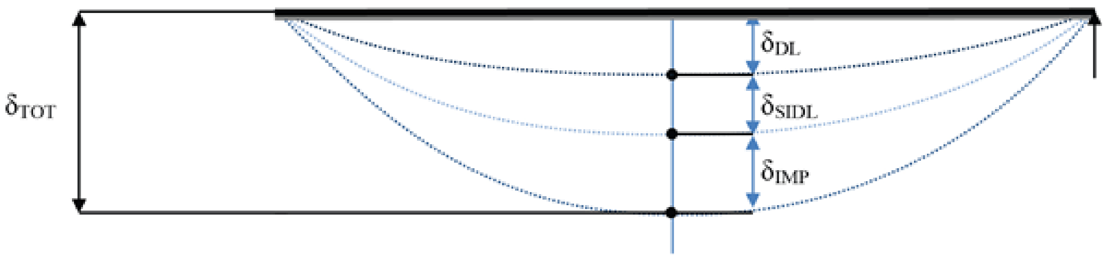



**Figure 4-56. Visual interpretation of the load sequence and the associated deflections for an edge beam**

It is emphasised in the documents that the point in the construction programme when the cladding is to be fixed to the structure is important from the tolerance management perspective. This is because deviations experienced after the cladding is installed must be incorporated within the cladding fixings. In other words, the cladding system should be capable of absorbing deviations due to its self-weight and any other load applied afterwards. During the serviceability design, the load sequence is agreed between the consultant and contractors so that the components are connected to the structure, primarily the responsibility of the cladding contractor.

The importance and the impact of the load sequence in tolerance management is demonstrated through an example given by one of the interviewees. It is assumed that the dead load deflection of an edge beam is 10 mm, the deflection due to the installation of a lightweight cladding is 5 mm, the deflection due to the weight of the finishes is 15 mm and the imposed load deflection is 5 mm. Given that deflections are cumulative and should be arithmetically added together, the total deflection of this edge beam will be 35 mm. In this example, the cladding system is fixed first and then the finishes are installed. Hence, the cladding will not experience the 10 mm dead load deflection because that has already occurred before the installation of the cladding. This means that the cladding will experience the deflection due to its self-weight (i.e. 5 mm), the weight of the finishes (i.e. 15 mm) and imposed loads (i.e. 5 mm), which is 25 mm in total. If the assembly process were different in such a way that the finishes were installed first and then the cladding, only the deflections due to the cladding self-weight and the imposed loads would need to be incorporated in the fixings of the cladding. This means that the cladding has to be capable of absorbing a deflection of 10 mm.

#### 4.4.1.6 Step Six: Communicating Tolerance Requirements/Risks

The interviewees highlighted the communication of tolerance requirements/risks as the most important step in their tolerance management process. The consultant aims to communicate the identified tolerance risks and their consequences before or during the construction in a simple language to other parties who may not be fully familiar with the terms and concepts that the consultant typically uses. In case three, the risk can then be addressed before responsible contractors for those risks are appointed to the project or can be properly communicated to them before their involvement in projects.

In this consultancy, the engineers produce various documents that include tolerance information as the project moves forward. A review of these documents demonstrates that some information relating to loadings, deflection limits and building movement can be found in them. However, the Tolerance and Deflections report is the document that unifies all the information related to tolerances. The purpose of the Tolerance and Deflections report is to communicate the tolerance information in one single document. I its content is as follows:

- Structural concepts (e.g. various types of loads, building movement);
- Explanation of various sources of variations (i.e., manufacturing/fabrication, setting out, erection, building movement, etc.);
- Tolerance classes, the associated combined deviation analysis for each class and the selected class of tolerance;
- The consequences of building movement on non-structural components;
- Tolerance analysis;
- Permissible deviations in structural members and the acceptable limits of deviations for the cladding system;
- A list of reference documents that define permitted deviations of the structural works.

If the achievement of a tolerance requirement on site is assumed by the engineers to be onerous, the actions needed to attain such a requirement will be specified in the report. For instance, in one of the projects, there was a need to enhance the capacity of the slab in order to limit deflections. This was to ensure that the slab and edge beam would not deflect to an unacceptable extent when subjected to the weight of the cladding. It was then recommended in the Tolerance and Deflections report that a reinforced concrete upstand beam be incorporated into the concrete slab.

The information provided in the document should be used mainly by the architect and the designers to give adequate allowance for the combination of dimensional and geometric deviations (e.g. setting out, manufacturing, construction and building movement), according to the engineers.

Furthermore, the consultant uses a novel method of visualising the geometric deviations of the structural members. The purpose of this method is to investigate the impact of deviations on non-structural components. For example, in one of the consultant’s projects, the envelope of the building was comprised of precast cladding intermixed with glazed/curtain wall elements. It has been explained in the Tolerance and Deflections report that, at the gable ends, pre-cast panels are positioned edge to edge. The initial design developed by the Cladding Subcontractor was to maintain a consistent 20 mm joint width between the panels. Such joint width is influenced by three parameters, according to the report, namely: (a) the rotation of the panels due to a vertical deflection in the edge beam, (b) fabrication deviations and (c) erection deviations. As a result of such parameters, there is a risk that panels may physically clash. Figure 6-57 demonstrates how the deflection in the edge beam can lead to the clash of panels. The red colour represents the panels before deflection and the green colour represents the panels after deflection.

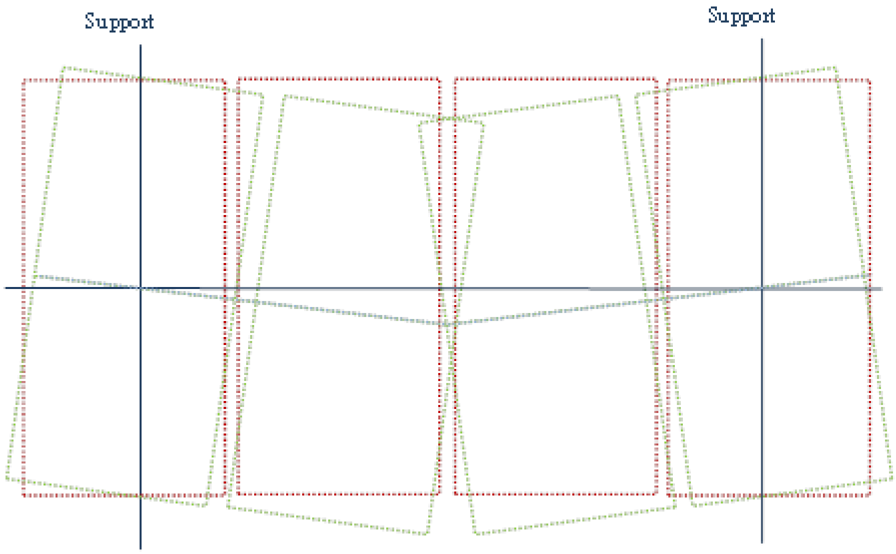



**Figure 6-57. Arrangement of pre-cast panels before and after being subjected to deflection**

To maintain a 20 mm clearance between panels, the impact of the sources of deviations should be analysed. In Figure 6-58, the arrangement of pre-cast panel joints has been given. The fabrication, erection and deflection deviations have been visualised to illustrate whether the components would clash or whether there would be a gap between them. Most importantly, the accumulation of deviations based on the assembly process has been demonstrated. This means that the fabrication tolerances (marked as 1) of the panels are shown first. Then the erection tolerance has been considered and added to the fabrication tolerance using the Root Sum Square method. Eventually, the deflection tolerances due to the weight of the panels have been added to prior deviations arithmetically.

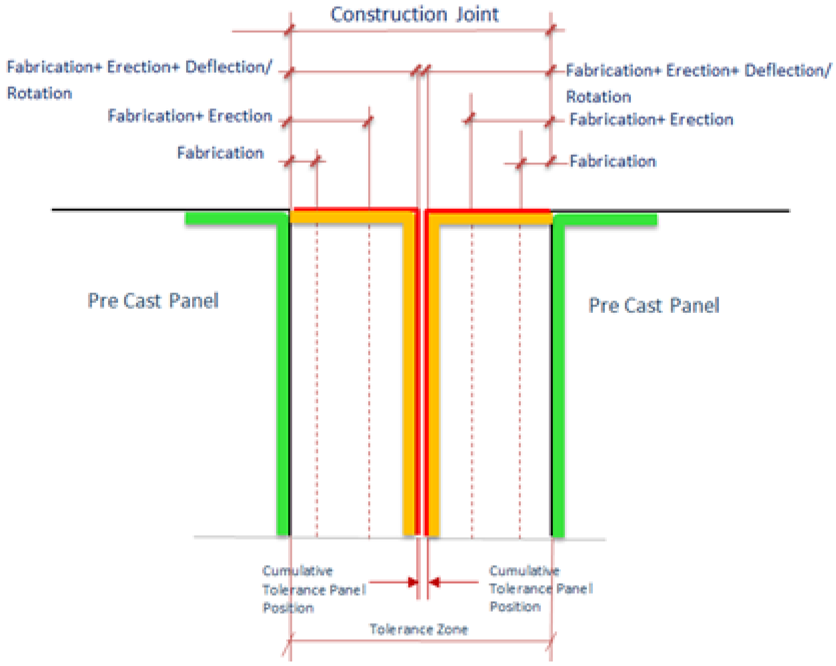



**Figure 6-58. Visualisation of the sources of deviations affecting a joint between pre-cast concrete panels (adopted from Tolerance and Deflection design note used in case three)**

Given that the consultant has chosen the normal tolerances for this case, the extreme position of the panels is first calculated by using a combination of statistical and worst-case methods. The fabrication tolerance of each panel is ± 3 mm according to the cladding manufacturer, the erection tolerance of each panel is ±6 mm according to the cladding subcontractor, and the setting-out tolerance of each panel is ±5 mm according to British Standards Institution (1990). Also, the consultant determines the maximum vertical deflection at the slab mid-span to be ± 1.5 mm. The red line in Figure 6-58 represents the combination of deviations and illustrates how deviations can affect the clearance between the two panels.

The tolerance analysis is performed using Root Sum Square method and worst case method. It transpires that the deviation of the position of each panel can be 10 mm.

In the worst-case scenario, if the deviation of the position of both adjacent panels would be 10 mm towards each other, the joint would then be closed. As a result, the consultant suggested that an increase in the joint width at the gables should be considered to accommodate the potential rotation of the panels positioned adjacent to each other.

#### 4.4.1.7 Step Seven: Performing Tolerance Compliance Control

The consultant documents the site visits and the identified tolerance problems in the structural frame as part of the Site Visit report. This report is complemented with photographs and marked drawings. For example, in one of the Site Visit reports, it is explained that the Project Engineer has recognised that the cantilevered entrance canopy requires alignment as it is visibly deflected. Moreover, the consultant in this report highlights the area in which tolerance problems are likely to occur and which should be controlled before the work progresses. For example, in one project, the consultant has recommended that deviations in the level of roof steel beams should be measured by the contractor before installation is completed.

#### 4.4.1.8 Step Eight: Analysing the Identified Tolerance Problems

In case of any excessive deflection of a structural member from what was predicted by the structural analysis, the consultant investigates whether there was a mistake in the structural design. All the analyses are then documented in the 'site visit report'. For example, in one project the consultant was informed by the principal contractor that the structural frame had deflected by up to 30 mm at a free-end cantilever under its self-weight, whereas the consultant had calculated that the anticipated deflection under the self-weight condition would be limited to 4.60 mm. Therefore, it was evident that the deflection realised on site was more excessive than that calculated. Eventually, the consultant's analysis demonstrated that the frame structure as designed was adequate and that the problem had been caused by the erection process of the frame.

### *4.4.2 Summary of the Tolerance Management Mechanism Performed by the Consultancy in Case Three*

In case three, a relatively advanced practice of tolerance management by an engineering consultancy explored. The steps taken by the consultant for managing tolerances were presented. The steps were: performing a serviceability analysis, selecting the class of tolerances, identifying tolerance requirements/risks, collectively finding realistic deflection limits, holding a trade-off between the cost of the structure and cladding system, selecting load sequences, communicating tolerance requirements/risks, performing tolerance compliance control and analysing the identified tolerance problems. It was demonstrated how visual aids can be used to make the impact of deviations transparent to all parties and how tolerance risks/requirements could be identified and communicated to mitigate tolerance risks and reduce lead times in the field. In Figure 6-59, the identified mechanism is presented. Note that Figure 6-59 is based on the author's understanding and it is not documented by the consultant itself.

It was perceived that the mechanism practiced and steps taken by the consultant can be connected to the PDCA cycle, explained in section 2.7.1. Performing serviceability analysis, selecting the class of tolerances, identifying tolerance requirements/ risks, finding realistic limits collectively, and selecting load sequences are all about establishing an understanding of tolerance requirements, and collecting data based on which a plan can be developed to achieve tolerance requirements. In other words, these steps account for the 'plan' in the PDCA cycle.

The communication of tolerance requirements/ risks is about communicating the necessary actions that need to be taken to achieve tolerance requirements and mitigate tolerance risks. Therefore, this step corresponds with the 'do' in the PDCA cycle.

Performing tolerance compliance control is about collecting data from site (inspection, measurement) to investigate whether the identified tolerance requirements have been achieved. Therefore, this step corresponds with the 'check' in the PDCA cycle.

Unlike the conventional practice of tolerance management observed in case one and two, the mechanism practiced by the consultant does not end after performing the tolerance compliance control and continues to analysing tolerance problems. Although the consultant misses more systematic mechanism by which the reoccurrence of the encountered tolerance problems can be avoided, this can be considered as a starting point to ensure occurred tolerance problems do not reoccur. This step is expected to continuously improvement the tolerance management practice of the consultant. Therefore, it is inferred that this step corresponds with 'act' in the PDCA cycle.

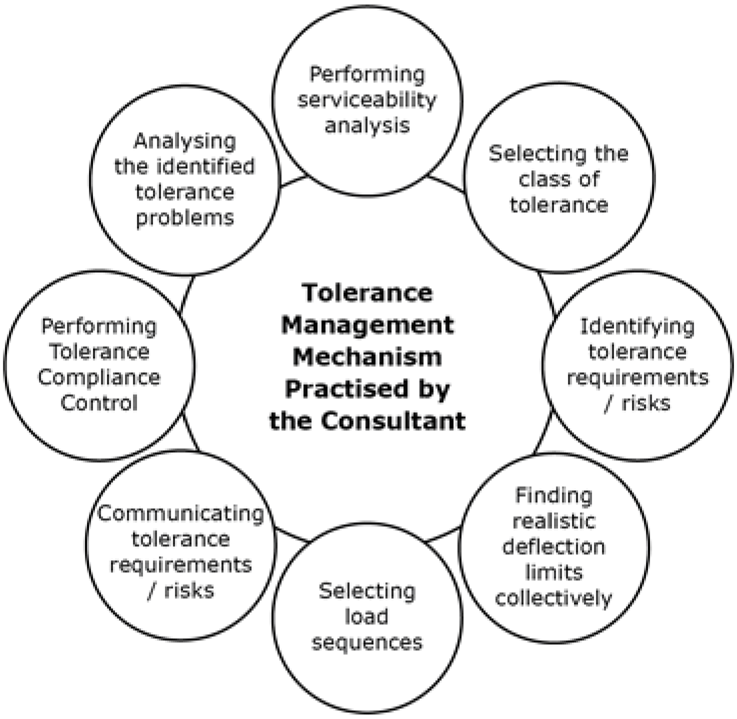



**Figure 6-59. The tolerance management mechanism practiced by the engineering consultant**

## 4.1 Summary

In this chapter, the empirical studies are presented and analysed. More specifically, current practice of tolerance management, tolerance problems in construction projects, and an advanced practice of tolerance management is presented. The first two cases helped the researcher to gain an understanding of the current mechanism of tolerance management, mainly at the site level. Such understanding includes how tolerances are co-ordinated and communicated between parties, and how the compliance of the achieved accuracy with the specified limits is verified. The purpose of the empirical studies in the third case was to explore the best practice of tolerance management performed by an engineering consultant. In this chapter, fifteen tolerance problems identified in cases one and two are described. The purpose behind the identification of those tolerance problems was to understand: (a) what a tolerance problem actually means; (b) what types of tolerance problems may occur on site, and (c) what the adverse effects of tolerance problems are.

## 4.2 Discussion

In case one and case two, there are methods (e.g. tolerance compliance measurement on site) and documents (e.g. Quality Check Sheets, specifications, drawings) that contribute to management of tolerances. However, the review and analysis of those methods and documents content that they should be used in a more systematic way and should be more focused on planning of tolerances. It can be argued that less attention to tolerance planning is paid in case one and two and tolerance problems are resolved on an ad hoc basis during construction. In case three, more attention is paid to tolerance management at the design stage to proactively identify tolerance requirements and risks. Moreover, the documents (e.g. tolerance and deflection report) and methods (e.g. communicating tolerance requirements/risks) used in case three have been developed specifically to avoid tolerance problems.

# CHAPTER 5: **ROOT CAUSES OF TOLERANCE PROBLEMS**

In this chapter, the root causes of the tolerance problems found during the empirical studies are identified and examined. As discussed in Section 2.6, despite the root causes of tolerance problems having been covered in the literature review, there remain restrictions that help to obscure these root causes. It is important to perform root cause analysis in this research in order to gain an in-depth and comprehensive understanding of these causes before developing a solution to improve the current practice of tolerance management. Therefore, this chapter particularly contributes to fulfil the first objective of this research, which is obtaining a comprehensive understanding of the current practice of tolerance management and tolerance problems. Although the root causes presented in this research are limited to two cases, presumably these can give an indication of the root causes of tolerance problems that occur across the industry. In this chapter, the approach used to identify and categorise the root causes of the identified tolerance problems is first explained. The root causes of the tolerance problems in cases one and two are then presented. This is followed by a discussion on the main findings.

## 5.1 Approach to Categorise the Root Causes of Tolerance Problems

There are a wide range of tools and approaches for root cause analysis. The approach integrated into the Fishbone diagram was adopted to identify the root causes of tolerance problems. The Fishbone diagram, invented by Kaoru Ishikawa in 1968, is a graphical tool to explore, sort and display the root causes of problems (Mobley, 1999). The principles of the Fishbone diagram help to better understand root causes of the problem, perceive the relative importance of different root causes, and recognise the areas where problems lie. The major drawback of this approach is that it can be subjective and limited by the experience and knowledge of who is deploying it (Barsalou, 2015). The principles of the Fishbone diagram are as follows (Andersen & Fagerhaug, 2006):

- The problems should be clearly described;

- A large surface with adequate space should be used to generate root causes. The problem should be written at the right end of a large arrow;
- The main category of the root causes of the problem, called root cause type, should be identified and written at the end of the branches connected to the large arrow;
- All root causes that belong to a main category should be written in the applicable branch;
- The analysis should continue until the most likely root causes for the stated problem are identified.

Root cause analysis when using the Fishbone diagram is categorical (Mobley, 1999). The categorical approach reveals all the possible root causes that can contribute to the problem (Mobley, 1999). The benefits of this approach helps academics and practitioners to: (a) consider all the possible root causes of a problem, (b) speed up the root cause analysis for the similar type of problems by providing predefined categories for possible root causes, and (c) use a consistent and uniformed terminology when investigating root causes for the problems with the same nature (Heuvel et al., 2014).

The steps, followed in this research to find the root causes, are explained next.

#### ***Description of the Identified Tolerance Problems (Step One)***

The first step includes the description of the identified tolerance problems. This can be found in Section 4.1.3 for case one and Section 4.2.3 for case two.

#### ***Creation of the List of Root Causes for Tolerance Problems Identified from the Literature and Interviews (Step Two)***

A list of root causes for tolerance problems was developed from the literature (see Table 2-9). Moreover, one of the questions in the interviews was "what are the root causes of tolerance problems in construction?". The interviewees state that the lack of communication of tolerance information between designers and construction teams, the lack of training, poor workmanship and human errors, incorrect work method, and inability to anticipate the building movement accurately are the root cause of tolerance problems. The root causes mentioned during the interviews have been already found in the literature except 'incorrect work method', which was added to the list.

***Root Cause Analysis for each of the Tolerance Problems Identified in Case One and Case Two (Step Three)***

The tolerance problems identified in cases one and two were analysed separately to find their root causes. The root cause analysis for each tolerance problem in case one is presented in Appendix J and the root cause analysis for each tolerance problem in case two is presented in section 5.2. The analysis for each problem continued until most of its root causes, if not all, had been explored. This step helps to verify the list of root causes collected from the literature and interviews. Five new root causes were identified, namely 'inconsistency between tolerance requirements of the project and its budget', 'ineffective decision-making techniques for tolerances', 'an incomplete outline specification given by the client', 'incorrect types of construction methods', and 'special causes'.

Note that the root cause of 'training' was found in the literature and during the interviews but was not allocated to a specific tolerance problem. This is because this root cause is indeed inherent in all the identified tolerance problems. Moreover, the root cause of 'inconsistent language across the industry to specify tolerances' was not identified from analysing the tolerance problems. Rather, it was perceived by comparing the terms used in documents reviewed in two cases and the literature.

Two root causes relevant to reference documents were found in the literature, namely 'inefficacious reference documents' and 'over-reliance on reference documents'. During the root cause analysis for the identified tolerance problems, it was not perceivable that ineffective reference document per se can lead to tolerance problems but over-reliance on such reference documents and subsequently specification of incorrect tolerance values can result in tolerance problems. 'Specification of unrealistic tolerance values' is another root cause for tolerance problems identified in the literature. However, during the empirical studies, it was observed that tolerance values are often adopted from reference documents. Therefore, again, the over-reliance on such reference documents eventually leads to specification of unrealistic tolerance values and should be considered as a root cause.

Two root causes related to Quality Control were found in the literature: 'poor tolerance compliance control' and 'ineffective Quality Control documents'. The latter so-called root cause seems very broad and the analysis of the identified tolerance problems shows that 'ineffective Quality Control documents', which is a subset of 'poor tolerance compliance control', is the thorough root cause.

‘Negligence of tolerances during the tender process’ appears to be another root cause in the literature. The analysis of the identified tolerance problems shows that ‘an incomplete outline specification given by the client’ is one of the reasons that leads to such negligence. Therefore, ‘an incomplete outline specification given by the client’ is considered as a thorough root cause for tolerance problems.

Table 5-28 shows the full list of the identified root causes through the literature review and empirical studies, and whether those root causes have been found from the empirical studies carried out in this research and/or literature review.

**Table 5-28. List of the root causes found in the literature and empirical studies**

| NO. | ROOT CAUSES | LITERATURE | EMPIRICAL DATA COLLECTION |
|---|---|---|---|
| 1 | Poor communication of tolerance information | X | X |
| 2 | Incomplete contract terms between general contractor and subcontractors | X | X |
| 3 | Deficiencies in the project procurement systems | X | X |
| 4 | Poor tolerance coordination | X | X |
| 5 | Inconsistency between tolerance requirements of the project and its budget | | X |
| 6 | Ineffective decision-making techniques for tolerances | | X |
| 7 | Insufficient and fragmented tolerance information in specifications | X | X |
| 8 | An incomplete outline specification given by the client | | X |
| 9 | Inconsistent language across the industry to specify tolerances | X | X |
| 10 | Ignorance of tolerance accumulation when specifying tolerances | X | X |
| 11 | Over-reliance on reference documents | X | X |
| 12 | Unforeseen building movement | X | X |
| 13 | Ineffective Quality Control documents | X | X |
| 14 | Deficient measurement instruments | X | X |
| 15 | Incorrect types of construction methods | | X |
| 16 | Poor workmanship | X | X |
| 17 | Inferior design of connections | X | |
| 18 | Deficient training | X | X |
| 19 | Special causes (e.g. poor weather conditions, tool breakdown) | | X |

### *Categorisation of the Root Causes of Tolerance Problems (Step Four)*

After performing the root cause analysis for each tolerance problem, the author attempted to group the similar causes on the list and create the root cause types for them, as the principles behind the Fishbone diagram require. An example of such attempt is the research work undertaken by Chen (2007), who uses the approach integrated in the Fishbone diagram to perform the root cause analysis for interface issues in built environment, and groups the root causes of interface issues into six categories.

The root cause types and their subsets in this investigation were iterated several times due to difficulties in (a) distinguishing clear, defined borders for each root cause, and (b) deciding under which root cause type the identified root causes should be positioned. Eventually, the root causes of tolerance problems were clustered into seven categories (i.e. root cause types), namely: Organisation, Tolerance Specification/ Tolerances in Specifications, Regulations, Quality Control Systems, Work Method/ Workmanship, Training, and Special Causes. An example of difficulty to define clear borders is 'an incomplete outline specification given by the client' which can arguably be under the root cause type 'Organisation'. These root cause types are the key factors that cause tolerance problems.

In Table 5-28, the first six root causes (no. 1 to 6) are related to communication, contracts, procurement systems, coordination between parties, project budget and decision making techniques, hence, those root causes are considered under the root cause type of Organisation. The next four root causes (no. 7 to 10) are related to information in specifications, language used in specifications, methods used to specify tolerances, hence, they were placed under the root cause type of Tolerance Specification/ Tolerances in Specifications. The next two root causes (no. 11 to 12) are related to reference documents, hence, Regulation was considered to be the root cause type for them. The next two root causes (no. 13 to 14) are related to Quality Control so they were placed under the root cause type of Quality Control Systems. The next three root causes (no. 15 to 17) are related to work methods and workmanship, so the root cause type of Work Method/Workmanship was selected for them. Training and Special Causes were selected as independent root cause types because they could not be considered under any other category.

***Visualising the Entire Root Causes and Root Cause Types Using the Fishbone Diagram (Step Five)***

As shown in Figure 5-60, the root cause types were written at the end of the branches emanating from the large arrow. All root causes that belong to a root cause type were attached to the main branches. Eventually, all the root causes and root cause types are visualised in Figure 5-61.

*Generalisation of the Root Causes of the Tolerance Problems Identified in Cases One and Two (Step Six)*

The root causes under each category were generalised, that is, root causes were expanded and defined based on the consolidated findings from analysing root causes of each tolerance problem and literature review without considering those root causes in the context of a specific tolerance problem and case. This was to gain a deeper understanding of the root causes in cases one and two and it was not meant to generalise those root causes to the entire industry. The generalisation of the root causes is presented in Section 5.2.

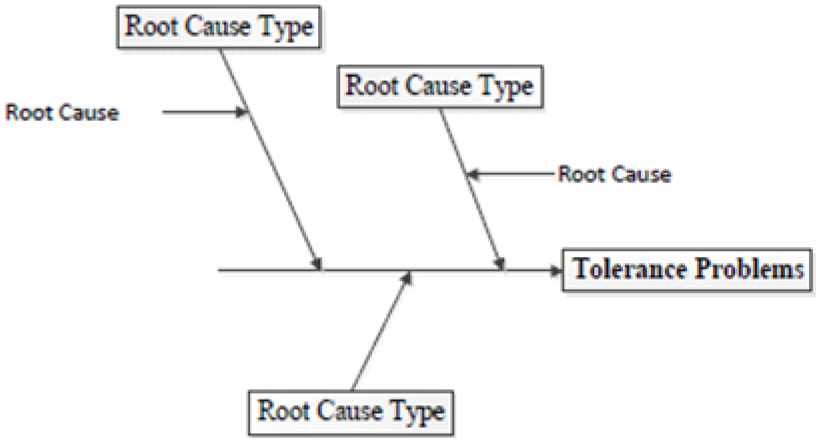



**Figure 5-60. Structure of the Fishbone diagram used in this research**

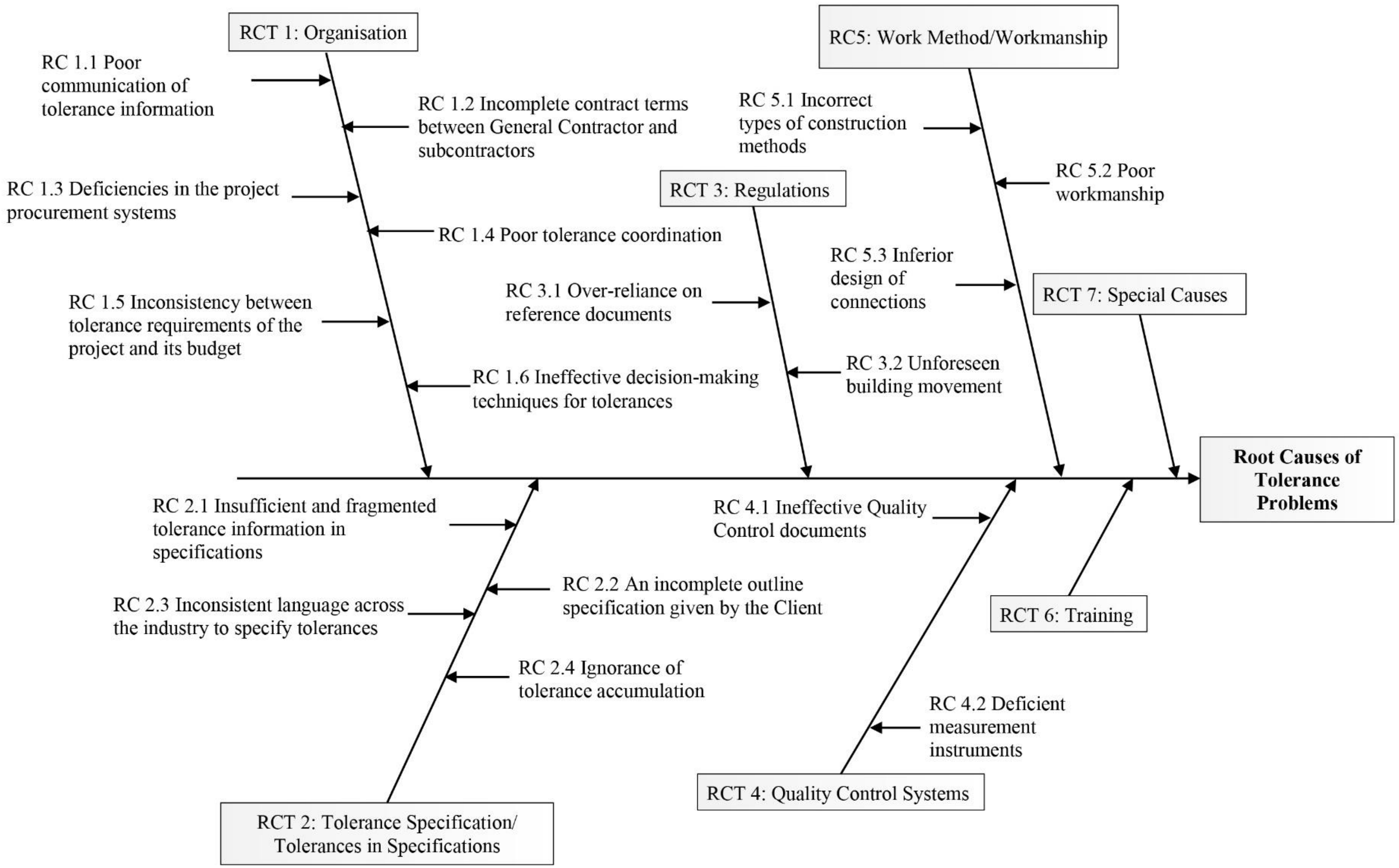



**Figure 5-61. Root causes of tolerance problems in construction**

## 5.2 Root Cause Analysis of the Tolerance Problems Identified in Cases Two

### Root Causes of Tolerance Problem 1 (Structural Steelwork and Doorway)

***Root Cause 1.1 Poor communication of tolerance information***

In case two, there was no information in the design documents or specifications to indicate that parallelism of stanchions is essential to ensure that electrically operated shutter doors will fit in the doorways. Also, neither of the parties involved in the assembly, namely the steel, cladding, and door subcontractors raised such tolerance risk and communicated the importance of the parallelism in doorways.

Generally, the communication of tolerance information in case two was relatively deficient. This is because only when the external site engineer was inspecting the structure, the information related to tolerances was communicated and discussed. In fact, the only information that the engineer was communicating was whether deviations in the orientation of columns and deviations in the position of the base plates comply with the limits stated in British Constructional Steelwork Association (2010), and if not, how to modify them and make them within limits.

***Root Cause 1.4 Poor tolerance coordination***

The steel and cladding subcontractors were procured in the project as one party. The general contractor trusted that these two subcontractors would perform the tolerance coordination between themselves (according to interviewees in case one). However, it turned out that there is not any coordination between these two and they acted entirely as two separate trades (according to interviewees and observations in case one). Moreover, in this case, the Senior Engineer of the general contractor was finding tolerances from the British Constructional Steelwork Association (2010) and informing the corresponding trades about their permitted deviations. However, he did not perform any tolerance analysis and did not attempt to coordinate tolerances between the trades. As a result, neither of parties was aware of the required parallelism tolerance of the primary and secondary steel frame.

***Root Cause 1.5 Inconsistency between tolerance requirements of the project and its budget***

The researcher observed that the general contractor was trying to keep the project costs as low as possible. For example, the structural designer had tried to use steel and ancillaries as little as possible. As a result, the two sides of the doorways are neither connected to each other nor they are fixed to the ground, that is, they are free standing. These made the rectification process difficult because by aligning one side of a cladding rail, the other side was becoming out of alignment. Moreover, in the contract between the general contractor and the steel subcontractor, there was a clause stating that the subcontractor can employ a site engineer when erecting the steelwork. However, the general contractor refused to have the site engineer full time available on site to inspect the steelwork. These actions were to cut down the project costs but resulted in a tolerance problem.

***Root Cause 2.1 Insufficient and fragmented tolerance information in specifications***

The specification of steelwork in case two is limited to the generic information replicated from the standards and does not have any information about the necessity of having the columns, stanchions, and PFCs aligned within particular deviation limits to ensure that the shutter doors fit in the doorways with ease.

***Root Cause 3.1 Over-reliance on reference documents***

Subcontractors hand over their work in conformance to the existing reference documents. The permitted inclination for columns according to the British Constructional Steelwork Association (2010) in case one is 11 mm. However, the site engineer and general contractor came to a conclusion that this tolerance is stringent (not achievable) for this project given the length of the building, number of columns, and capability of the steel subcontractor. The general contractor then allowed the inclination of 15 mm. It can be argued that this amount of inclination for columns in doorways is not suitable. This is because if the column at one side is orientated 15 mm towards west, and the column at the other side of the door is orientated 15 mm towards the east, the door must be fitted between two columns with 30 mm difference in their orientation.

***Root Cause 4.1 Ineffective Quality Control documents***

There was no Quality Check Sheet this case. As a result, neither of the parties was aware that parallelism of the stanchions in doorways with a tight tolerance is necessary. The site engineer, as usually, inspected the columns and rectified them. He then exceptionally measured the deviations in the position of the stanchions in both sides of the doors and noticed that stanchions are considerably out of alignment.

***Root Cause 5.2 Poor workmanship***

An experienced steel subcontractor would predict that how the stanchions and cladding should be erected to ensure the fit and functionality of the shutter doors.

***Root Cause 5.3 Inferior design of connections***

The designer had not accounted for the functionality of the connection between the steelwork and doors. The connection is functional if the cladding rail and stanchions in doorways are parallel. However, the designer did not devise appropriate connections to accommodate deviations due to stanchions being out of alignment.

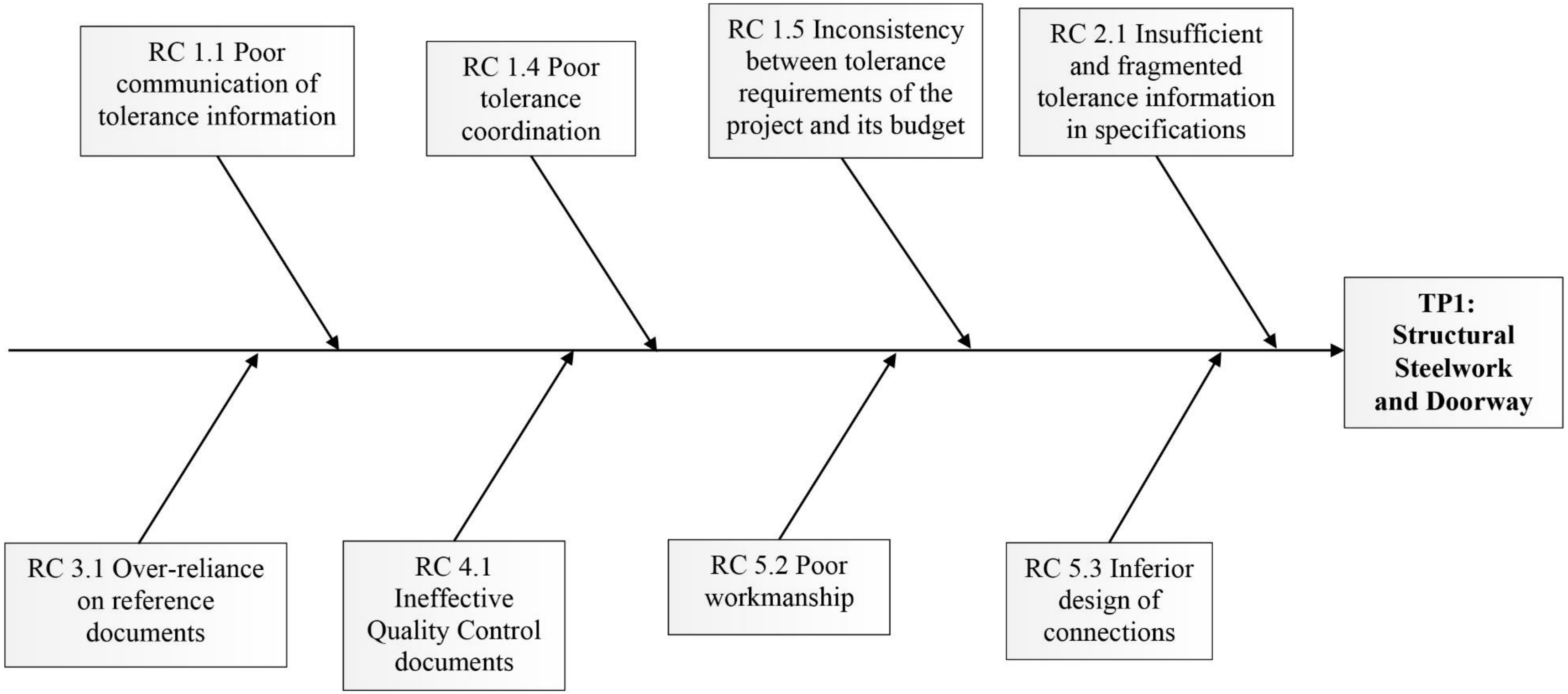



**Figure 5-62. Root causes of tolerance problem 1 (structural steelwork and doorway)**

## Root Causes of Tolerance Problem 2
## (Wavy Purlins)

### *Root Cause 1.1 Poor communication of tolerance information*

The problem with the wavy purlins started from the first phase of the steelwork. The cladding subcontractor and steel erector had been discussing the problem several times. However, the general contractor had not been updated about the problem on the roof. When the cladding subcontractor at some point realised that the steel subcontractor denies rectifying the purlins and its ancillaries, the supervisor of cladders started to liaise with both the steel subcontractor and main contractor. If the general contractor had been informed about the tolerance risk earlier, the rectification of the purlins had probably not been left to the last minute and the problem could have been avoided.

### *Root Cause 1.2 Incomplete contract terms between the general contractor and subcontractors*

A document, called 'Method of Erection', was issued by the steel subcontractor. There is a statement in this document that "the feature steelwork & stringers are to be co-ordinated into the structure as the work progresses". One may conclude from this somewhat vague clause that the installation of the purlins had to be coordinated with the adjacent members. However, it is not clear who should perform the coordination and how.

### *Root Cause 1.4 Poor tolerance coordination*

On the roof, the fit of the panels entirely depends on whether the tolerances of the panels and purlins are compatible and deviations are accommodated in their joints. Hence, it is important to coordinate the tolerances of the two trades, namely the steel subcontractor and cladding subcontractor. However, although these two parties were procured as one party, it seemed there was no tolerance coordination between them. The steel subcontractor installed the purlins without paying attention to the steel contractor's argument that the purlins are wavy and hence it is not possible to properly tie in the panels.

***Root Cause 1.6 Ineffective decision-making techniques for tolerances***

The general contractor was being informed about the issues on site by the subcontractors in the daily or weekly meetings. The risk in the joint between purlins and roof panels was not mentioned until the cladder could not carry out his work and he brought it to the discussion in a weekly meeting. The reason that this issue was not pointed out earlier in one of the daily meetings is that the participant from the steel gang was not a decision maker. He could only receive the next-day plan and did not have any right to make decisions. Especially in this case, it was important to make decisions whether to cut all the purlins and their threaded bars off and resupply them or whether to adjust them on the roof. Apart from this, it is speseculated that the steel and cladding subcontractor were not willing to argue in front of the general contractor as they were trying to pretend that they are genuinely one party and united. Hence, the cladder overlooked the problems with purlins in earlier phases of the steelwork until the risk of having leaks due to the gaps between the purlins and panels became high.

***Root Cause 2.1 Insufficient and fragmented tolerance information in specifications***

Neither in the Structural Steel Statement nor in the Performance Specification, there is any hint about how to install the purlins and avoid the risk of having them wavy. There is not even one single piece of information about the relevant reference document that the steel erector should follow to ensure the correct installation.

***Root Cause 3.1 Over-reliance on reference documents***

As far as it is known, there is only one industry guidance available for tolerances of the secondary steelwork including light gauge steel purlins and sheeting rails, called "Best Practice for the Specification and Installation of Metal Cladding and Secondary Steelwork". However, neither in the structural steelwork specification nor other, there is a reference to this guidance. The guidance could have supported the designer to select a correct system for the secondary steelwork on the roof rather than choosing the purlins with Z sections (explained in Section 4.2.3.2), which were chosen incorrectly.

***Root Cause 4.1 Ineffective Quality Control documents***

According to the researcher's observations and interviews, none of the staff from the general contractor visited the roof to control the purlins until the cladding subcontractor made an argument. One of the reasons for the lack of quality control is that the general contractor did not have any Quality Check Sheets to be aware of this risk and to ensure that the purlins are straight and within limits.

***Root Cause 5.2 Poor workmanship***

Poor workmanship is another cause of the problem with the purlins. If the steel subcontractor was competent, they would have thought whether the cladding subcontractor would be able to install the roof panels between the purlins. Moreover, when the steel erectors stand on cherry pickers for long hours under inclement weather conditions, they would pay less attention to the quality of their work, mainly if there is no inspection over the erected elements.

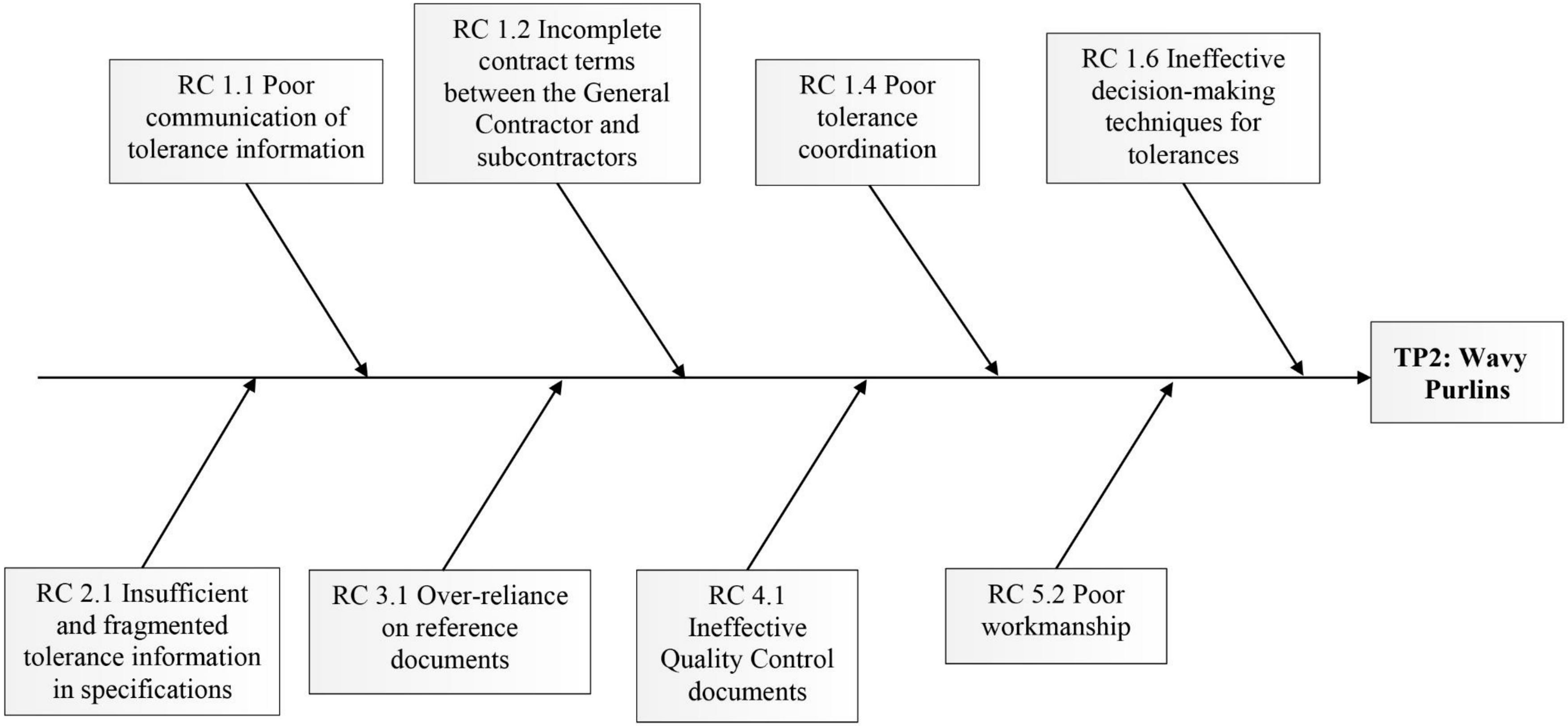



**Figure 5-63. Root causes of tolerance problem 2 (wavy purlins)**

## Root Causes of Tolerance Problem 3
## (Lack of Fit in the Steelwork)

### *Root Cause 1.1 Poor communication of tolerance information*

The site engineer was measuring deviations of the steelwork but there was no communication about the impact of those deviations to the rest of the project. Arguably, one of the reasons is that the site engineer thought the structure will be consistently built and the whole structure will incline towards one direction. When the general contractor and the steel subcontractor decided to erect the steelwork in two pieces and then connect them, there was no communication with the site engineer to check whether that is a correct decision to make.

### *Root Cause 1.2 Incomplete contract terms between the general contractor and subcontractors*

There is a document called 'Design for Construction' developed by the steel subcontractor. This document delineates the responsibilities and commitments of the steel subcontractor during the design and construction. It states that "the start point and direction of erection should be established at the design stage". Based on this statement, a fundamental question remains about why the cost of building the crane platform and the time needed to build it had not been negotiated earlier and had been left to the last minute. If it had been discussed earlier, the general contractor would have applied for the contingency money, and the platform could have been built before it would be needed. As a result of this decision (i.e., erecting the building in two pieces), the columns 31B, 31C, 31 E and 31 G are out of plumb and their deviations are not accepted according to the national regulations British Constructional Steelwork Association (2010).

The document of 'Design for construction' also indicates that "the work undertaken should fully comply with both the client's requirements and all statutory regulations". In spite of this statement, there are several columns in the last phase of the steelwork which their position and plumbness do not comply with British Constructional Steelwork Association (2010). In other words, the steelwork does not satisfy both the client's requirements and statuary regulations. This document does not clarify what the penalty is for breaching this clause of the contract and the general contractor did not take any legal action.

***Root Cause 1.5 Inconsistency between tolerance requirements of the project and its budget***

As part of the contract with the steel subcontractor, the general contractor could have asked for an engineer to monitor the steel erection on site continuously. Obviously, this would somewhat yield to an additional cost for the general contractor. Not having an internal site engineer resulted in a steelwork which is considerably out of tolerance, the lack fit on the roof, and a relatively high amount of rework.

***Root Cause 1.6 Ineffective decision-making techniques for tolerances***

In a weekly meeting, the general contractor and the steel subcontractor decided to split the project into two pieces rather than building a crane platform. They made this decision only because they intended to save some money and time. However, they did not take account of the risks and pros of such action, more specifically, nor do they examine the risks of tolerance issues. The researcher believes that this is because participants in the weekly meetings did not have adequate knowledge about the tolerance risks.

***Root Cause 4.1 Ineffective Quality Control documents***

There was not any Quality Control Sheet that makes the parties aware of the permissible deviations through which two sides of the building could have been connected without any laborious and time-consuming adjustment.

***Root Cause 5.1 Incorrect types of construction methods***

The decision of erecting the steelwork in two pieces was wrong from the tolerance point of view. Even in this work method, there might be some other ways to make the deviations of both sides more compatible to each other. Nevertheless, no suggestion was raised by any of the two involved parties.

***Root Cause 5.2 Poor workmanship***

If the operatives of the steel subcontractor were more conscious about tolerances, they would erect the second erected side as accurate as possible using the tools and equipment in hand (according to interviewees in case two). However, the second erected side had the worst deviations compared to the rest of the structure. This may be because the steel subcontractor intended to take its employees to a new project and it was vital for them to finish as soon as possible. The higher speed of erection made the steel erectors more prone to make errors.

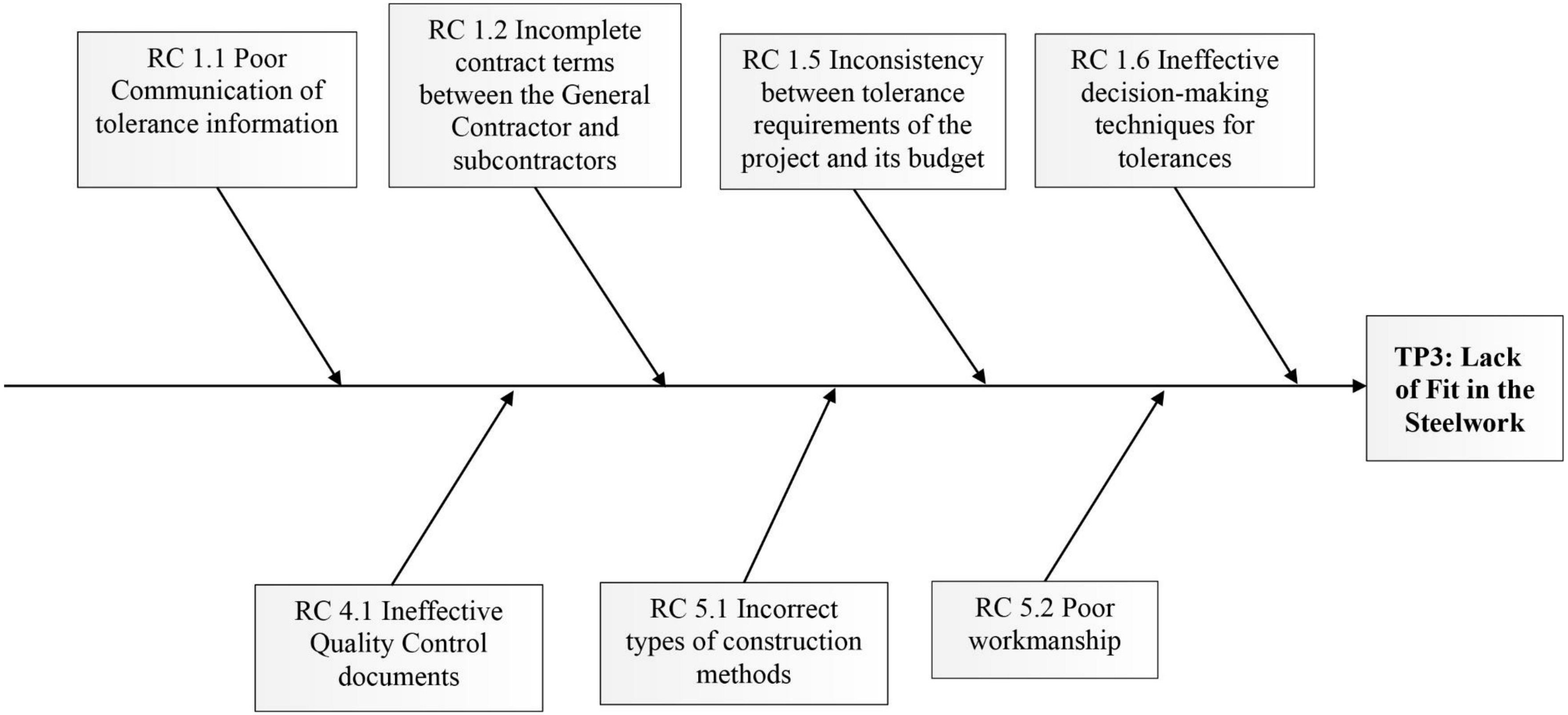



**Figure 5-64. Root causes of tolerance problem 3 (lack of fit in the steelwork)**

## Root Causes of Tolerance Problem 4
## (Lack of Fit for the Personnel Doors)

***Root Cause 1.4 Poor tolerance coordination***

Despite the cladding and steel subcontractors' bid for the project as one party, it is apparent that the designers of these two parties had not accounted for each other's deviations to ensure the fit and functionality of the personnel doors. More specifically, the designer of the cladding subcontractor did not account for the deviation of the interfacing columns to avoid physical conflict. There is no provision of any appropriate clearance or jointing technique between the columns and doorframes to accommodate the columns' deviations.

***Root Cause 2.1 Insufficient and fragmented tolerance information in specifications***

The document 'Structural Design Statement' identifies some risks related to the steelwork and some of them can be regarded as tolerance risks. One of the identified risks is about the secondary steelwork, which includes door framing and window framing. There is no any further explanation about this risk. The only mitigation strategy for this ambiguously-stated risk is "allowance/ estimate secondary steel provided." This so-called mitigation strategy raises intriguing questions regarding the amount of allowance and the method to provide the allowance.

Moreover, in this document, the connections with brickwork/ block work, wind posts, shutter framing, composite panel etc. have been considered as risky. However, neither of these components has been used in case two. These show that the risk assessment in this document has not been specifically for this project.

***Root Cause 4.2 Deficient measurement instruments***

It turned out that the cladding subcontractor had measured the distance between the posts making the doorframes at the bottom and top using a conventional measuring tape. However, they ignored the fact that the doorframes actually can be oriented either to left or right side even though when those distances are the same and measuring tape is inappropriate to check the squareness of the doorframes.

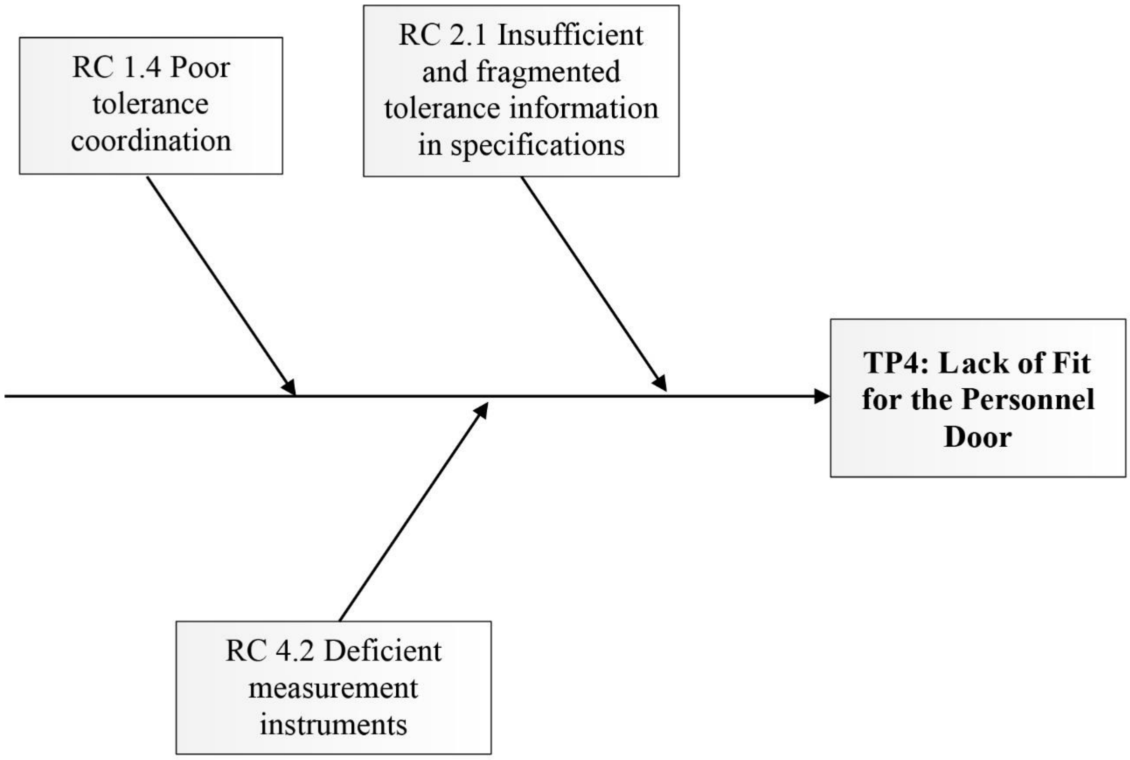



**Figure 5-65. Root causes of tolerance problem 4 (lack of fit for the personnel door)**

## Root Causes of Tolerance Problem 5 (Parallel Flange Channels and Abutting Components)

***Root Cause 1.4 Poor tolerance coordination***

When two or more components are tolerance-wise related to each other and contractually separated parties provide them, the General Contractors in this project was trying to coordinate tolerances of those components. However, in this specific situation, the steel subcontractor was responsible for designing and installing the steel columns, Parallel Flange Channels (PFC), struts and bolts. That is, the General Contractor did not have to get involved for coordinating tolerances between the both primary and secondary steelworks as both are provided by the steel subcontractor. Hence, the steel subcontractor should have recognised that in this assembly the tolerance for the clearance between the flashing and cladding rail (PFC) is important. The deviation of the abutting elements should not reduce the minimum required clearance which is necessary to spin the bolts and put the threads up. However, this tolerance requirement of the minimum clearance in this assembly had been neglected.

***Root Cause 2.4 Ignorance of tolerance accumulation***

The combined deviations of the components involved, and their impact on the required clearance between the flashing and the cladding rail, had been overlooked in the joint.

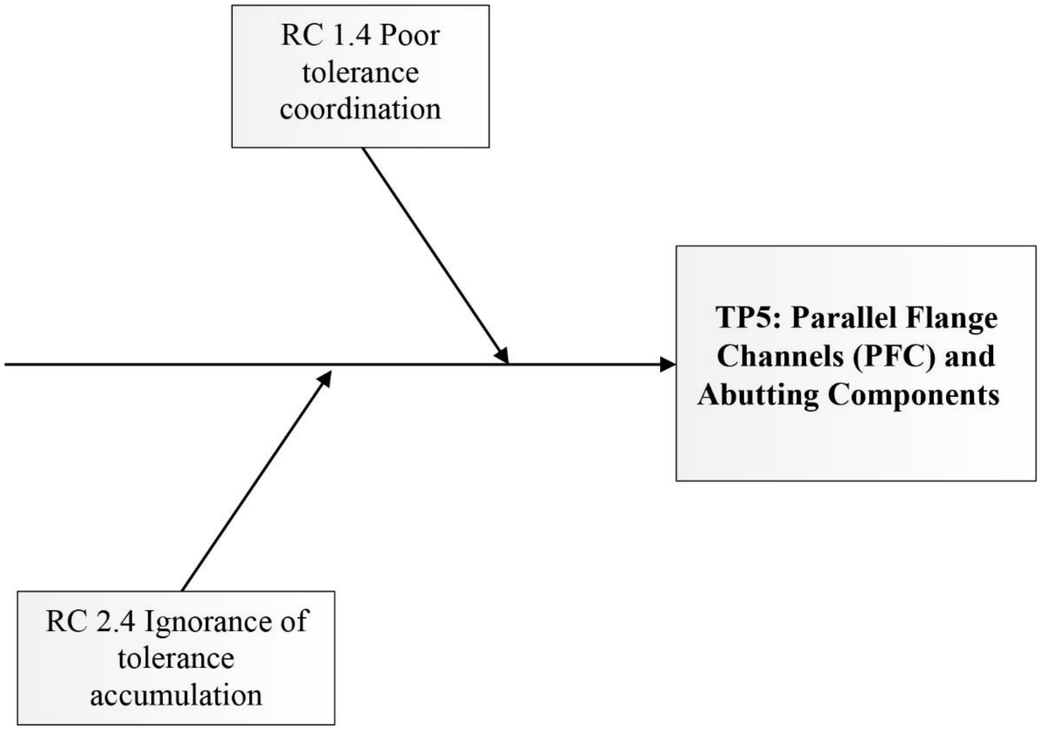



**Figure 5-66. Root causes of tolerance problem 5 (Parallel Flange Channels and abutting components)**

## 5.3 Generalisation of the Root Causes of the Tolerance Problems Identified in Cases One and Two

In this section, the seven root cause types, followed by the root causes under each category (root cause type), are explained in detail. As mentioned in Section 5.1.3, five root causes (i.e. inconsistency between tolerance requirements of the project and its budget, ineffective decision-making techniques for tolerances, an incomplete outline specification given by the client, incorrect types of construction methods, and special causes) were found in comparison to the literature. The remaining root causes were found during both the literature review and the empirical studies in case one and two. Reference is made to the tolerance problems (TPs) in which the root causes were observed.

**Root Cause Type 1: Organisation**

***Root Cause 1.1 Poor Communication of Tolerance Information***

A series of documents, methods and techniques are directly/indirectly used as part of the tolerance management activities to facilitate the communication of tolerance information between parties (explained in Chapter 4). However, (a) existing documents (i.e. drawings, specification, design notes) mostly do not adequately include tolerance information, and (b) existing design documents (i.e. drawings and Building Information Models) and design techniques (e.g. design review meetings) do not effectively transfer the information to other trades (TP8, TP9 in case one, in TP1, TP2, TP3 in case two). This results in poor communication of tolerance information. Poor communication of tolerance information hinders disciplines and trades to make realistic decisions about tolerance values collectively and is a root cause for a significant portion of tolerance problems (TP8, TP9 in case one, TP1, TP2, TP3 in case two).

***Root Cause 1.2 Incomplete Contract Terms between the General Contractor and Subcontractors***

The contractual documents (e.g. specifications) often do not explicate the tolerance information. More specifically, contracts and specifications may include ambiguous tolerance information and they often try to transfer the risk of financial loss for the potential tolerance conflicts to other parties (explained in Chapter 4; TP1 in case one; TP2, TP3 in case two). Also, in the specifications and design notes, subcontractors often make the general contractor, or other trades, responsible for obtaining the information regarding the size and position tolerances of other components. In fact, the specifications often do not clarify who the other parties are precisely and do not specify what they should do to avoid tolerance conflicts (TP1in case one; TP2, TP3 in case two).

***Root Cause 1.3 Deficiencies in Project Procurement Systems***

There is an overlap between design and construction in some of the most commonly used project delivery methods. Given the tight schedule for development of the design in such delivery methods, the general contractor is often not able to capture all the information from the subcontractors until a few weeks before they start their work on site. When negotiating with subcontractors to develop the designs, tolerances are often not at the top of the general contractor's agenda. Tolerances may only be discussed at the end of the design cycle or right before starting on site. It is too late at this stage to make any changes to the type of components, design of connections and work method to mitigate tolerance risks (TP10 in case one).

Moreover, the operatives are paid based on the amount of work completed per. This means that the quicker they work, the more money they can make. This arguably makes the operatives more prone to make mistakes (TP7 in case one).

***Root Cause 1.4 Poor Tolerance Coordination***

When considering tolerances of a single component, the coordination between the designer and the subcontractors on site is important for ensuring that the assigned tolerances are realistic and constructible. When considering tolerances of two or more components, which make a sub-assembly and which are connected tolerance-wise, the coordination between the involved construction trades and design disciplines is essential. This is to ensure that the tolerances of the components are compatible (i.e. they have the same level of dimensional and geometric accuracy), the deviations are absorbed in their connections, and sub-assemblies made of two or more mating components meet the functional objectives (e.g. there is no leak) (explained in Chapter 2). However, there are two causes which impair the tolerance coordination between parties.

The design and construction teams are often aware of the accuracy of their own components and fabrication tolerances. However, the first cause is that those teams may not be aware of the deviations due to the building movement (TP1, TP6 in case one; TP1, TP2, TP4, TP5 in case two). The second cause is that the coordination of tolerances requires an amalgamation of practical and theoretical knowledge. The theoretical part is related to the tolerance analysis (e.g. combined deviation analysis) and structural analysis (i.e. building movement), and the practical part is associated with the erection/assembly of components and in-situ work whilst considering the required tolerances. Surveyors, architects, design managers, and project managers often have either a practical or theoretical background; there is a lack of personnel who possess both skills and can effectively supervise the tolerance coordination. Also, those appointed to these roles are usually overwhelmed with their regular tasks. In complex projects, especially, the number of tolerance issues is often larger than simpler projects, however, the personnel cannot undertake the task of tolerance coordination due to their tight schedule and the complicated nature of the activities needed for tolerance coordination (TP8 in case one; TP1, TP4, TP5 in case two).

### *Root Cause 1.5 Inconsistency between Tolerance Requirements of the Project and its Budget*

It was observed that subcontractors make every effort to reduce the costs, to focus on their own tasks, and to avoid seemingly time-consuming and costly coordination (e.g. design coordination), which would prevent the tolerance conflicts or reduce their negative impacts. The inconsistency between tolerance requirements of the project and its budget may eventually increase the project costs as a result of incurred rework and workflow interruption (TP1 in case two). Moreover, general contractors may bid for cheaper work methods or may not ask for full time site engineer to decrease the construction cost and be more competitive but these measures may lead to tolerance problems (TP1, TP9 in case one; TP3 in case two).

### *Root Cause 1.6 Ineffective Decision-Making Techniques for Tolerances*

There are some specific procedures (e.g. design review meetings and progress meetings) in a project to facilitate the decision-making process and the communication between parties in regard to tolerances. Key decisions concern the identification and mitigation of tolerance risks and the modification of occurred tolerance problems. However, these procedures often cannot identify the entire scope of tolerance conflicts, and they often cannot successfully play their preventive role when addressing tolerance problems (explained in Chapter 4). The following two causes make the decision-making tools ineffective as they in some causes cannot successfully play their preventive role when addressing tolerance risks.

The first cause is that in the meetings, various issues are discussed. The issues concerning tolerances make up a small proportion of the discussions. Even though those issues (e.g. loadings, deflection, concrete shrinkage) may be discussed, the risk of their adverse impact on the geometric accuracy of the building and solutions to mitigate their negative impact may not be directly taken into account by the attendees (TP1 in case one; TP2, TP3 in case two). Second, general contractors may follow the instructions given by architects and consultants, rather than the subcontractors, even when solutions to mitigate tolerance risks are propounded by the subcontractors (TP8 in case one). Nevertheless, the subcontractors work with their components day in/day out and have more knowledge of the risks associated with their components than others (according to interviewees in case one). As a consequence, even though tolerance risks may be identified by decision making techniques, optimal decisions may not be adopted (TP2 in case two).

**Root Cause Type 2: Tolerance Specification / Tolerances in Specifications**

***Root Cause 2.1 Insufficient and Fragmented Tolerance Information in Specifications***

The tolerance information in specifications is often inadequate and fragmented, resulting in tolerance incompatibilities, confusion, and disputes between the parties (explained in Chapter 2). These issues arise because specifications often do not develop the required tolerance information by considering the specific conditions of the project (TP1 in case one; TP2 in case two). They are often adopted from the reference documents or are replicated from similar previous projects (explained in Chapter 2; TP9, TP10 in case one; TP1, TP2, TP4 in case two). Moreover, specifications only revolve around tolerances of the offered component and do not account for the tolerances of other components that, tolerance-wise, are related to the component in question (explained in Chapter 2; TP6, TP8 in case one).

***Root Cause 2.2 An Incomplete Outline Specification Given by the Client***

The outline specifications may require the general contractor to use more expensive and/or time-consuming work methods or components with more stringent tolerances. Conversely, the client may not specify the work methods and the type of component in the outline specification which are necessary to achieve tolerance requirements. As a result, the general contractor tendering projects sometimes bases the cost of the works on the cheaper and quicker work methods and not on the methods that meet the client's requirements regarding geometric accuracy (e.g. the flatness of concrete slabs). Consequently, the general contractor will have to call upon the contingency fund for remedial actions to satisfy the requirements after being awarded the project (TP1 in case one).

***Root Cause 2.3 Inconsistent Language across the Industry to Specify Tolerances***

It is evident from the academic writings and industry documents that a consistent terminology to ascribe tolerance information is lacking within the industry (explained in Section 2.6, Section 4.1.2.1 and 4.3). This means that there is no commonly used lexicon by which practitioners can specify tolerances in a way that shared understanding can be established. An example would be the vague distinction between different types of tolerances (i.e. size, form, orientation, position) both in the academic writing and industry documents, whereas those characteristics are well defined in manufacturing through standard languages such as Geometric

Dimensioning and Tolerancing (The American Society of Mechanical Engineers, 2009). This lack of a consistent terminology in construction leads to confusion and hinders the practitioners and researcher in reaching agreements to find solutions to tackle problems, because a shared in-depth understanding about the terms related to tolerances may not be achieved (explained in Chapter 2).

***Root Cause 2.4 Ignorance of Tolerance Accumulation***

Designers typically use chain dimensioning in their drawings, in which all dimensions in their drawings are connected head-to-tail as chains, without considering tolerances (explained in Chapters 2 and 4). This results in the potential for accumulated deviations. If the construction trade follows the chain in layout, deviations in size or position can accumulate to the final dimensions. As a result of the accumulated deviations of preceding components, it can be onerous to fit the final component (explained in Chapter 2; TP3, TP5 in case two).

**Root Cause Type 3: Regulations**

***Root Cause 3.1 Over-Reliance on Reference Documents***

Subcontractors often hand over their work in conformance to the existing standard tolerances specified in the reference documents. The reference documents define basic rules and criteria for tolerances of individual components and are essential as a starting point to adopt tolerance values (explained in Chapters 2 and 4). However, they do not guarantee, despite the outputs being within the tolerance, that tolerance conflicts (e.g. the lack of fit) will not occur (explained in Chapter 2; TP10 in case one). This is because:

- The reference documents do not consider the worst-case scenario where component variations in size are at their extremes, or where components are placed in an extreme location. In this situation, although components are within their tolerances, the connection may not function properly (explained in Chapter 2, TP6);
- There are still many construction tolerances that do not have industry standards attached to them (e.g. manufacturing / fabrication / setting-out of fins, secondary steelwork) (explained in Chapter 2; TP10 in case one; TP2 in case two);
- The tolerances stated in the reference documents are sometimes too stringent or too lenient, and designs based on them may not be

constructible and achievable (explained in Chapter 2; TP1 in case one; TP1 in case two).

***Root Cause 3.2 Unforeseen Building Movement***

Reversible or permanent geometric changes in the form of a building structure, due to unforeseen movements, may lead to tolerance problems. The structural designer and specialist subcontractors have to calculate the building movements just as consciously as they do the forces and stresses. However, determining building movement is a sophisticated task, particularly in complex buildings. This is because there is no current code of practice, as there is for most other aspects of the design process, and not even a broad consensus on the validity or accuracy of predictions of movements (explained in Chapter 2; TP8, TP9 in case one). The lack of information at the design stage can make the calculation of building movement even more difficult (TP8, TP9 in case one).

**Root Cause Type 4: Quality Control Systems**

***Root Cause 4.1 Ineffective Quality Control Documents***

It was observed that some of the defects in the non-structural elements are detected by subsequent subcontractors. This problem occurs because the Quality Check Sheets may not adequately cover all elements, materials, and products that need to be checked or may not cover all dimensional and geometric features that need to be measured. As a result, the site management may not be aware of: (a) what dimensional and geometric features of components and assemblies should be controlled, and (b) how they should be controlled (TP1, TP2, TP3 in case two).

***Root Cause 4.2 Deficient Measurement Instruments***

The instruments that are currently used to verify the compliance of tolerance requirements are not completely accurate. This shortcoming may result in unrealistic decisions due to not having the full and accurate measurements in hand.

**Root Cause Type 5: Work Method / Workmanship**

***Root Cause 5.1 Incorrect Types of Construction Methods***

The design of connections, the amount of building movement and many other factors that affect the dimensional and geometric accuracy of a building to a great extent, depend on the type of construction method. The selection of an inappropriate construction method increases the likelihood of tolerance problems (TP4 in case two).

**Root Cause 5.2 Poor Workmanship**

Poor workmanship is a typical cause of tolerance problems. Cost reduction often equates employment of less experienced workforce with lower salary expectations. These issues increase the probability that the accomplished work will not meet the quality requirements in terms of tolerances and will not function properly (TP1, TP2 in case two).

***Root Cause 5.3 Inferior Design of Connections***

The lack of precise data regarding the accuracy of components, the accuracy of fabrication and erection, and the building movement results in inferior design of connections, which in consequence cannot effectively absorb deviations (TP8, TP10 in case one; TP1 in case two).

**Root Cause Type 6: Training**

It is no exaggeration to state that knowledge regarding tolerances is undeveloped and reference documents are known as the only means to learn about tolerances during both design and construction. The general lack of adequate training, especially on how to identify and mitigate tolerance risks, has a cross-cutting influence on the emergence of tolerance problems.

**Root Cause Type 7: Special Causes**

Exceptional and unforeseen circumstances, such as inclement weather conditions, tool breakdown, etc., increase the risk of not achieving required tolerances. For instance, if concrete is poured on a rainy day, or the power float crashes, it is very likely that the flatness of the concrete surface finish will not be acceptable (TP5 in case one).

## 5.4 Summary

The integrated approach in the Fishbone diagram was adopted to find, sort and display the root causes of the identified tolerance problems during the empirical studies. The findings from the literature and empirical studies were used to generate a list of sixteen root causes for tolerance problems which were fallen into seven root cause types: Organisation, Tolerance Specification/Tolerances in Specifications, Regulations, Quality Control Systems, Work Method/Workmanship, Training and Special Causes.

Such a root cause analysis has established important findings that are explained as follows. First, the analysis presents a comprehensive list of root causes which resulted in tolerance problems in cases one and two. Such root causes also give an indication of reasons behind the reoccurrence of tolerance problems in other projects across the industry as well.

Second, five new root causes were found in comparison to the literature. Those root causes are 'inconsistency between tolerance requirements of the project and its budget', 'ineffective decision-making techniques for tolerances', 'an incomplete outline specification given by the client', 'incorrect types of construction methods', and 'special causes'.

Third, the identified root causes from the literature were refined and verified. For example, 'negligence of tolerances during the tender process' is a root cause found in the literature. However, the root cause analysis for the identified tolerance problems ascertain that the lack of tolerance information in the outline specification given by the client' is one of the causes of such negligence. Hence, 'an incomplete outline specification given by the client' was considered as a root cause. Similarly, the other root causes found in the literature were verified in the context of the identified tolerance problems to ensure that they are real root causes of those problems.

Above all, the comprehensive root cause analysis in this research provides a basis to develop a holistic process for tolerance management. More specifically, it helps a deeper understanding of where the root causes of problem with the current practice of tolerance management lays. The aim of tolerance management is to develop a method whereby the identified root causes can be tackled.

As it was discussed in Sections 3.4.4 and 5.4, the literature review, the root cause analysis and the empirical study three were instrumental to develop TMS. Table 5-29 shows the recommendations given in the literature to improve tolerance management, the findings from the empirical study three, and the corresponding responses to those recommendations/ findings in TMS. Table 5-30 shows the identified root causes, the countermeasure(s) in principle and practical their embodiment to tackles those root causes, and corresponding steps and parts developed in TMS to ensure those root causes are addressed. The parts and steps of the artefact, TMS, will be explained in Chapter 6 in more detail.

**Table 5-29. Recommendations in the literature to improve tolerance management and corresponding measures in TMS.**

| RECOMMENDATION | SOURCE(S) | CORRESPONDING MEASURE IN TMS |
|---|---|---|
| Appointment of the strategic / tactical committees. | Graves and Bisgaard (1999) | Appointment of the Strategic / Tactical Tolerance Management Committee |
| Appointment of the engineer / architect for tolerance coordination. | American Concrete Institute (2014) | Appointment of the Tolerance Coordinator |
| Tolerance management meetings should be held before and during construction. | Ballast (2007)<br>American Concrete Institute (2014) | Tolerance Management Meetings (pre-bid, pre-construction, construction) |
| Start of tolerance management from early stages of a project. | Precast/Prestressed Concrete Institute (2004)<br>Empirical study three | Identification of the Key Information in the Client's Brief and Concept Design |
| Calculation of building movement. | CIRIA (1983)<br>Empirical study three | Determination of Maximum Loads Acting on the Structure and General Deflection Criteria |
| Determination of class of tolerances to ensure stability and serviceability. | "A checklist on tolerances" (1974)<br>CIRIA (1983)<br>Empirical study three | Selection of Classes of Tolerances |
| Connections should be identified because tolerances of adjoining components should be taken into account. | Marguet and Mathieu (1998)<br>Ballast (2007) | Identification of Critical Connections and their Associated Risk Using Tolerance Interdependency Matrix |
| Tolerance risks should be identified at early stages of the project. | Marguet and Mathieu (1998)<br>Empirical study three | |
| Tolerance management should be a top-down approach in which tolerances in sub-assemblies are taken into account. | Marguet and Mathieu (1998)<br>Empirical study three | Identification of Critical Sub-Assemblies Using Tolerance Interdependency Network |
| Critical dimensions and positions should be specified. | British Standards Institution (1988a)<br>British Standards Institution (1990) | Identification of Key Characteristics of the Components/Sub-Assemblies |
| The type of tolerances should be specified. | Ballast (2007) | |
| Identification of tolerance risks. | British Standards Institution (1990)<br>American Concrete Institute (2014)<br>Ballast (2007)<br>Empirical study three | Tolerance Risk Assessment |
| Generation of solutions to mitigate tolerance risks. | British Standards Institution (1990)<br>American Concrete Institute (2014)<br>Empirical study three | |

**Table 5-29 Continued**

| RECOMMENDATION | SOURCE(S) | CORRESPONDING MEASURE IN TMS |
|---|---|---|
| Appropriate reference documents to adopt tolerance values should be selected. | American Concrete Institute (2014) | Selection of Reference Documents to Adopt Tolerance Values for the Identified Key Characteristics |
| Tolerance information should be collected from appropriate reference documents, manufacturers, designers, contractors and users. | Ballast (2007)<br>American Concrete Institute (2014) | Assignment of Tolerance Values for the Identified Key Characteristics |
| Characteristic Accuracy should be calculated for every permissible deviation. | British Standards Institution (1990) | Determination of Characteristic Accuracy |
| Tolerance analysis should be performed. | Mantripragada and Whitney (1998)<br>British Standards Institution (1990)<br>American Concrete Institute (2014)<br>Empirical study three | Evaluation of Combined Deviations (Tolerance Analysis) |
| Appropriate construction methods should be used to minimise sources of variations influencing Key Characteristics. | Vorlíček and Holický (1989)<br>Empirical study three | Reducing sources of variations influencing Key Characteristics. |
| Appropriate design of connections. | CIRIA (1983)<br>British Standards Institution (1990)<br>Precast/Prestressed Concrete Institute (2004)<br>Ballast (2007)<br>American Concrete Institute (2014) | Reducing impacts of variations influencing Key Characteristics |
| Determination of the sequence of assembly process. | "A checklist on tolerances" (1974)<br>Empirical study three | |
| Appointment of project members for tolerance management. | British Standards Institution (1990)<br>Precast/Prestressed Concrete Institute (2004) | Completion of the Tolerance Agreement and Design Form |
| Specification of tolerances based on process capability, functional requirements, and to ensure stability and serviceability. | "A checklist on tolerances" (1974)<br>British Standards Institution (1988b)<br>British Standards Institution (1990)<br>Craig (1996)<br>Mantripragada and Whitney (1998)<br>Precast/Prestressed Concrete Institute (2004) | |

**Table 5-29 Continued**

| RECOMMENDATION | SOURCE(S) | CORRESPONDING MEASURE IN TMS |
|---|---|---|
| The compatibility of the specified tolerances of adjoining components in sub-assemblies should be checked. | American Concrete Institute (2014)<br>Empirical study three | |
| Tolerance synthesis should be performed. | Mantripragada and Whitney (1998) | |
| A measurement plan should be created. | Craig (1996)<br>American Concrete Institute (2014) | Completion of the Tolerance Compliance Measurement Protocol |
| The responsibility for verification of tolerance requirements should be specified and communicated. | British Standards Institution (1990) | |
| Tolerance information should be translated into a simple language. | Costadoat et al. (2012) | Visualisation of Variations |
| Tolerance requirements should be specified in drawings. | CIRIA (1983)<br>Ballast (2007) | Incorporation of Tolerance Information in Drawings |
| Specifications is the main means to communicate tolerance requirements | CIRIA (1983) | Creation of Unified Tolerance Specification |
| The permitted deviations, the reference documents used and the method to verify tolerance compliance should be communicated through specifications. | Ballast (2007)<br>Empirical study three | |
| A document comprising of all tolerance information in the project (e.g. Tolerance and Deflection design note) should be compiled. | Empirical study three | |
| Deviations should be measured. | Vorlíček and Holický (1989)<br>Empirical study three | The Execution of the Tolerance Compliance Measurement |
| The impact of deviations on the functional requirements should be assessed. | Vorlíček and Holický (1989)<br>Craig (1996) | Record of Tolerance Compliance Measurement Results |
| Tolerance values should be assigned based on the realistic process capability. | "A checklist on tolerances" (1974)<br>British Standards Institution (1990)<br>Milberg (2006)<br>Empirical study three | Creation of A3 Reports<br>Creation of Tolerance Manual |

**Table 5-30. Root causes of tolerance problems, countermeasure(s) in principle and their practical embodiment to tackle those root causes, and corresponding measures in TMS to address the root causes**

| ROOT CAUSE | COUNTERMEASURE(S) IN PRINCIPLE | PRACTICAL EMBODIMENT | CORRESPONDING MEASURES (STEPS, PARTS) IN TMS |
|---|---|---|---|
| Poor communication of tolerance information | The tolerance information should be communicated in drawings and specifications. | The relevant tolerance information should be incorporated and communicated in drawings and specifications through a standardised guideline. | Visualisation of Variations<br>Incorporation of Tolerance Information in Drawings<br>Creation of Unified Tolerance Specification |
| Incomplete contract terms between general contractors and subcontractors | The contractual documents (e.g. specifications) should only include relevant information and should specify whose responsibility it is to deal with each tolerance requirement/risk. | There should be a set of steps by which tolerance requirements/risks are identified and it should be clarified whose responsibility it is to achieve tolerance requirements, and respond to those tolerance risks. Eventually, all the collected information, which is relevant to the project, should be presented in one contractually accepted document. | Tolerance Risk Assessment<br>Completion of the Tolerance Agreement and Design Form<br>Creation of Unified Tolerance Specification |
| Deficiencies in the project procurement systems | Parties should not be procured based on when information is needed from them for construction on site. It should be also taken into account whether tolerance information from certain parties is required earlier. | The connections with high tolerance risks should be identified and passed to the tendering team. Designers and construction trades responsible for components in the connections with high risks should be procured earlier. | Identification of the Key Information in the client's Brief and Concept Design<br>Identification of Critical Connections and their Associated Risk Using Tolerance Interdependency Matrix |

**Table 5-30 Continued**

| ROOT CAUSE | COUNTERMEASURE(S) IN PRINCIPLE | PRACTICAL EMBODIMENT | CORRESPONDING MEASURES (STEPS, PARTS) IN TMS |
|---|---|---|---|
| Poor tolerance coordination | Tolerances should be considered in sub-assemblies rather than for components only.<br>A member of the project who is aware of practical and theoretical aspects of tolerance management should take responsibility for tolerance coordination on the project. | Connections and sub-assemblies should be recognised in order to ensure that the tolerances of components involved in those connections and sub-assemblies are compatible.<br>There should be coordination between designers to ensure that the tolerances of components involved in sub-assemblies are compatible and that appropriate measures are taken in the design to avoid tolerance problems.<br>A new role, called tolerance coordinator, should be introduced. | Identification of Critical Connections and their Associated Risk Using Tolerance Interdependency Matrix<br>Identification of Critical Sub-Assemblies Using Tolerance Interdependency Network<br>Appointment of the Tolerance Coordinator |
| Inconsistency between tolerance requirements of the project and its budget | Contractors should bid on the project according to the captured tolerance requirements and risks. | A set of standardised steps and documents should be developed to capture tolerance requirement/risks and to plan how to achieve tolerance requirements and respond to tolerance risks. Therefore, contractors can bid on the project based on the measures needed to respond to captured tolerance risks/requirements. | Part one: Identification of Tolerance Requirements/Risks<br>Part Two: Planning the Achievement of Tolerance Requirements/Mitigation of Tolerance Risks<br>Organisational Design in Tolerance Management System |
| Ineffective decision-making techniques for tolerances | A forum, specifically to discuss tolerances should be provided. | A series of meetings from early stages of the project to the completion of construction should be held to discuss issues related to tolerances. | Tolerance Management Meetings |

**Table 5-30 Continued**

| ROOT CAUSE | COUNTERMEASURE(S) IN PRINCIPLE | PRACTICAL EMBODIMENT | CORRESPONDING MEASURES (STEPS, PARTS) IN TMS |
|---|---|---|---|
| Insufficient and fragmented tolerance information in specifications | The relevant tolerance information should be communicated in specifications. The tolerance information should not be limited to single components but should consider components that are connected tolerance-wise. | The reference documents from which tolerance values are adopted should be selected. Tolerance information (e.g. tolerance risks/requirements, tolerance values) for sub-assemblies should be collected. Eventually, a specification comprising all tolerance information relevant to a specific project should be created. | Selection of Reference Documents to Adopt Tolerance Values for the Identified Key Characteristics<br>Creation of Unified Tolerance Specification |
| An incomplete outline specification given by the client | The solution should help contractors to find tolerance information or give an indication of what information should be acquired from the client. | A list of key tolerance information should be given to general contractors to enable them to search for certain information in the outline specification or to acquire missing information from the client. | Identification of the Key Information in the client’s Brief and Concept Design |
| Inconsistent language across the industry to specify tolerances | A lexicon, in order to communicate tolerance information consistently, should be prepared. | Terms from manufacturing and mechanical engineering should be adopted and refined for tolerance management in construction. | Identification of Key Characteristics of the Components/Sub-Assemblies |
| Ignorance of tolerance accumulation | The existing methods in reference documents should be used to calculate the combined deviations. | A clear instruction to calculate combined deviations using the worst case and the root sum square methods should be given. | Evaluation of Combined Deviations (Tolerance Analysis) |
| Over-reliance on reference documents | There should be a mechanism whereby tolerance values can be determined if an industry standard does not exist for a material or for an element. Moreover, the main criteria in such a mechanism should be whether or not the assigned tolerance value adopted from a reference document ensures the functional requirement and whether it is achievable. | Appropriate tolerance values should be specified to satisfy functional requirements. The tolerance values can be adopted from reference documents, based on the experience of parties involved in the project, and on knowledge gained from previous projects. | Completion of the Tolerance Agreement and Design Form<br>Organisational Design in Tolerance Management System<br>Assignment of Tolerance Values for the Identified Key Characteristics<br>Creation of Tolerance Manual<br>Record of Tolerance Compliance Measurement Results |

**Table 5-30 Continued**

| ROOT CAUSE | COUNTERMEASURE(S) IN PRINCIPLE | PRACTICAL EMBODIMENT | CORRESPONDING MEASURES (STEPS, PARTS) IN TMS |
|---|---|---|---|
| Unforeseen building movement | Building movement should be considered from early stages of the project and should be considered as a tolerance risk. | The loads that will be applied to a building, the sequence of loading and the risk due to building movement should be taken into account. | Determination of Maximum Loads Acting on the Structure and General Deflection Criteria<br>Tolerance Risk Assessment |
| Ineffective Quality Control documents | Tolerance requirements and the way to satisfy those requirements should be stated in Quality Control documents. | Quality Control documents should include (a) the dimensional and geometric features of components that need to be controlled, and (b) details of how they should be controlled. | Completion of the Tolerance Compliance Measurement Protocol<br>The Execution of the Tolerance Compliance Measurement |
| Deficient measurement instruments | The inaccuracy of measurement instruments should be taken into account. | The type of measurement instrument, which implies the level of accuracy, should be decided. | Completion of the Tolerance Compliance Measurement Protocol |
| Incorrect types of construction methods | An appropriate construction method should be selected to satisfy tolerance requirements and to mitigate tolerance risks. | An appropriate work method should be selected to satisfy tolerance requirement specified by the client. Moreover, an appropriate work method (e.g. type of connections, load sequence) is a response to tolerance risks. | Identification of the Key Information in the client's Brief and Concept Design<br>Tolerance Risk Management |
| Poor workmanship | Risks associated with poor workmanship and their consequences for the accuracy of buildings should be recognised. | A standardised risk management process should be developed specifically for tolerances and this should account for the risks associated with poor workmanship. | Tolerance Risk Management |
| Deficient Training | Risks associated with deficient training and their consequences for the accuracy of buildings should be recognised. | A standardised risk management process should be developed specifically for tolerances and this should account for the risks associated with deficient training. | Tolerance Risk Management |
| Special Causes | Risks associated with special causes and their consequences for the accuracy of buildings should be recognised. | A standardised risk management process should be developed specifically for tolerances and this should account for the risks associated with special causes. | Tolerance Risk Management |

# CHAPTER 6: **TOLERANCE MANAGEMENT SYSTEM**

From the discussions in Chapters 1 and 2, it emerges that there is a need to develop a process for tolerance management in construction. This process should help practitioners to identify and prevent tolerance problems prior to construction, and it should also tackle the identified root causes of tolerance problems. For this purpose, a system, called Tolerance Management System (TMS), has been designed and developed. This chapter is to fulfil the second objective of this research, which was to develop a solution to improve tolerance management. The developed solution will then be evaluated (Chapter 7) to fulfil the third objective of this research, which was evaluation of the proposed solution. This chapter starts with a general overview of TMS and the change that it is expected to make in the construction industry. It then explains the design and development of TMS, and describes the steps of TMS in detail.

## 6.1 Introduction to Tolerance Management System

According to Hill (2012), a system can be defined as a set of independent elements (e.g. technologies, tools, information) that are joined together to deliver a mission. Similarly, Arbnor and Bjerke (2008) define system as a group of elements that work together to produce certain results. In view of this, in this research, a system, called Tolerance Management System (TMS), is developed. TMS consists of as a set of steps that are joined together to deliver a certain mission, which is achieving a consistency of identifying tolerance requirements/risks, preventing/mitigating adversarial impacts of tolerance risks on functionality and aesthetic of assemblies, and obtaining tolerance requirements in building constructions. The objective of TMS is to facilitate the coordination of tolerances among construction trades and designers in construction projects to deliver projects with the maximum value, and without any interruption in the workflow due to tolerance problems. TMS has been designed in a way that general contractors in particular can continually improve their practice of tolerance management over time.

TMS is divided into five parts, namely: identification of tolerance requirements/risks, planning the achievement of tolerance requirements/mitigation of tolerance risks, communication of tolerance information, tolerance compliance measurement, and learning and documentation. Figure 5-67 schematically represents TMS. Each part consists of a set of steps. In each step standardised techniques and documents, many of which are not absolutely new but should be considered as propriety of TMS, are proposed. In fact, they are mostly modified and standardised versions of existing techniques and documents across different domains of research (from engineering to management), which have been modified specifically for tolerance management in construction.

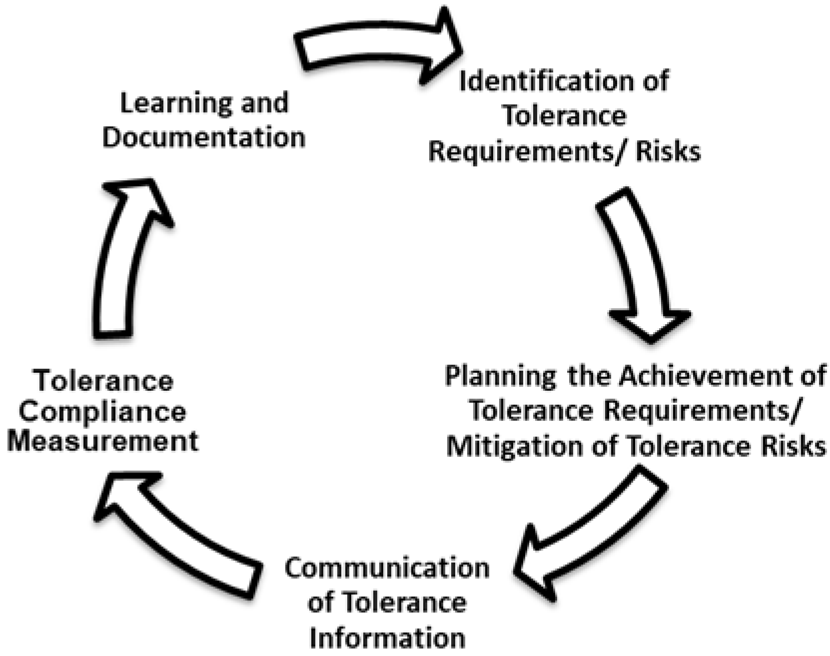



**Figure 5-67. Schematic presentation of Tolerance Management System**

## 6.2 Overview of Tolerance Management System

Figure 5-68[1] represents a typical practice of tolerance management in the industry, perceived during the empirical studies (i.e. observations, interviews, document review) and by reviewing the literature. As can be seen in Figure 5-68, first the tolerance requirements are specified based on the project objectives (e.g. the flatness required for surfaces), then tolerance values are adopted from reference documents. Contractors then attempt to comply with the specified tolerances, and eventually, the compliance of the achieved deviations on site with the specified

[1] The idea of creating Figure 5-67 was inspired by the PhD thesis of Dr. Glenn Ballard (Ballard, 2000) for explaining a traditional (push) planning system.

tolerances is verified. If it transpires that deviations of components do not fall within the permissible deviations, or assemblies do not function as intended due to deviations in their size and form (i.e. tolerance problems have occurred), the modification process starts. Once tolerance problems are fixed, this process of tolerance management is completed. In this process, "MUST" reflects the fact that when tolerance values are adopted from reference documents, the capability of the construction team to achieve the specified level of accuracy is often ignored.

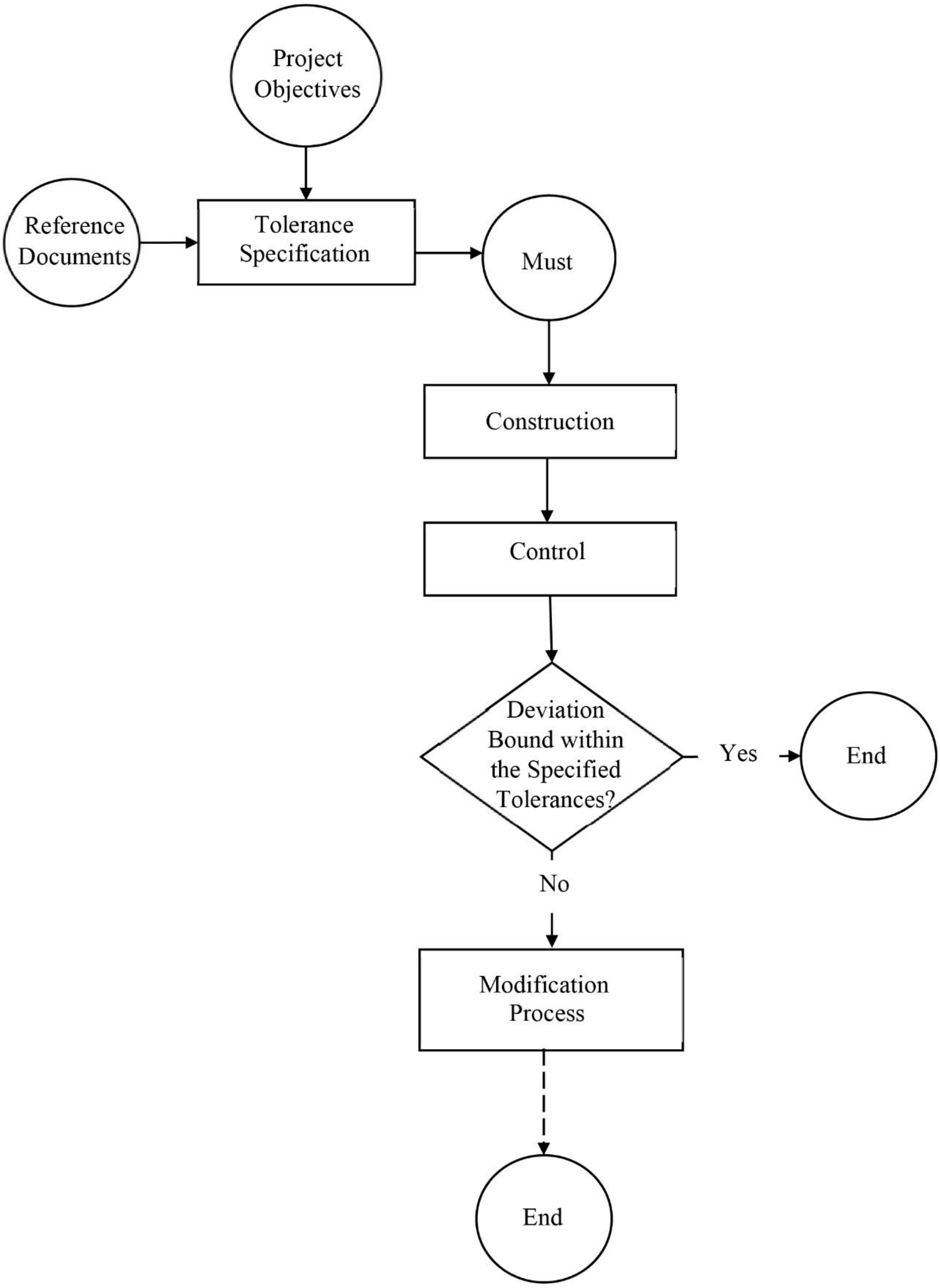



**Figure 6-68. Common practice of tolerance management in the construction industry**

Figure 6-69[2] illustrates how the conventional practice of tolerance management, presented in Figure 6-69, is replaced by TMS. In short, in TMS: (a) the expert knowledge, along with the collected information from reference documents and the captured client's requirements, are input into the process, (b) tolerance values are assigned after following a set of steps to ensure that the construction team can achieve them (i.e. the construction team is capable of achieving them), (c) the deviations of components and assemblies are checked to ensure they are within tolerance limits and they function and look as intended, (d) the findings and gained knowledge are documented and analysed, and (e) the knowledge gained and information collected are reused for future instances of TMS implementation. In this process, "CAN" represents the fact that by following TMS, the capability of the construction team to achieve the required level of accuracy is taken into account.

[2] The idea of creating Figure 5-68 was inspired by the PhD thesis of Dr. Glenn Ballard (Ballard, 2000) and the description of the Last Planner System®.

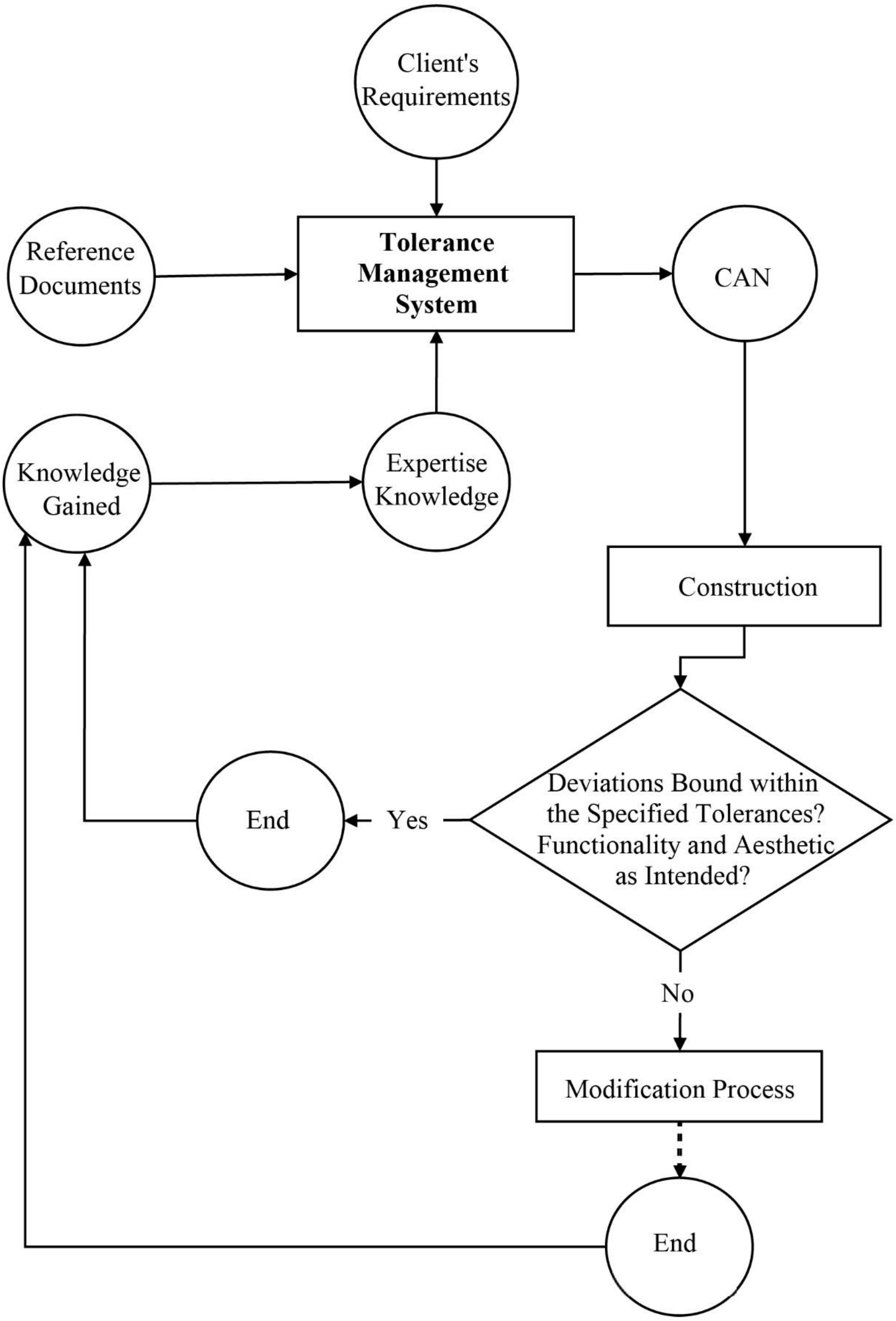



**Figure 6-69. Overview of Tolerance Management System**

In Figure 6-70, the steps and flow of information in TMS are presented. The arrows in Figure 6-70 represent the flow of information between steps. In Figure 6-70, the steps and flow of information in TMS are presented. The arrows in Figure 6-70 represent the flow of information between steps. As it was discussed in Section 2.4.4 and 5.4, the steps and elements of TMS demonstrated in Figure 6-70 come from (a) the review of the solutions to improve tolerance management not only in construction but also in manufacturing, and also (b) review of a relatively advanced practice of tolerance management in practice (case three). It was shown in Table 5-29 that how TMS has been designed to correspond to the findings from the literature and empirical studies. Moreover, it was discussed in section 5.4 that an effective solution for tolerance management should potentially tackle root causes of tolerance problems. Table 5-30 shows that the steps of TMS were developed in a way that they are countermeasure(s) to the root causes of tolerance problems.

It should be noted that TMS is not a linear process but some steps can be performed in parallel and some steps should be completed over time. In essence, TMS is an iterative and continuous process, even within a single project, in the way that tolerance information is gradually collected as more parties are involved in the project, and decisions made are tested as the work progresses. If a decision is reported to not be completely optimal, which means the modification process is still needed and/or the design intent regarding the aesthetic or function is not satisfied, the initial decision must be negotiated again and corresponding information needed for that decision should be re-collected.

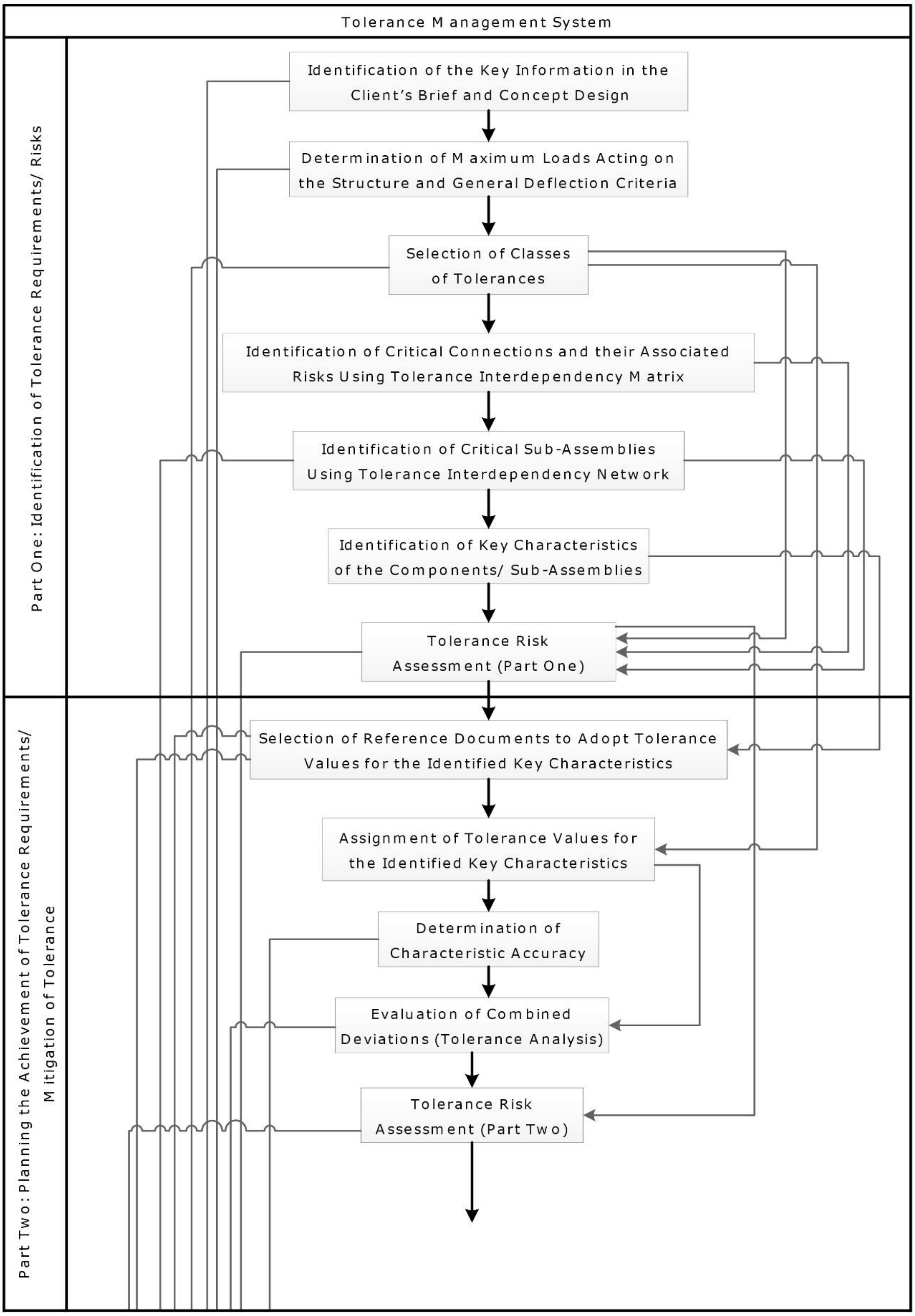



**Figure 6-70 Continued**

**Figure 6-70 Continued**

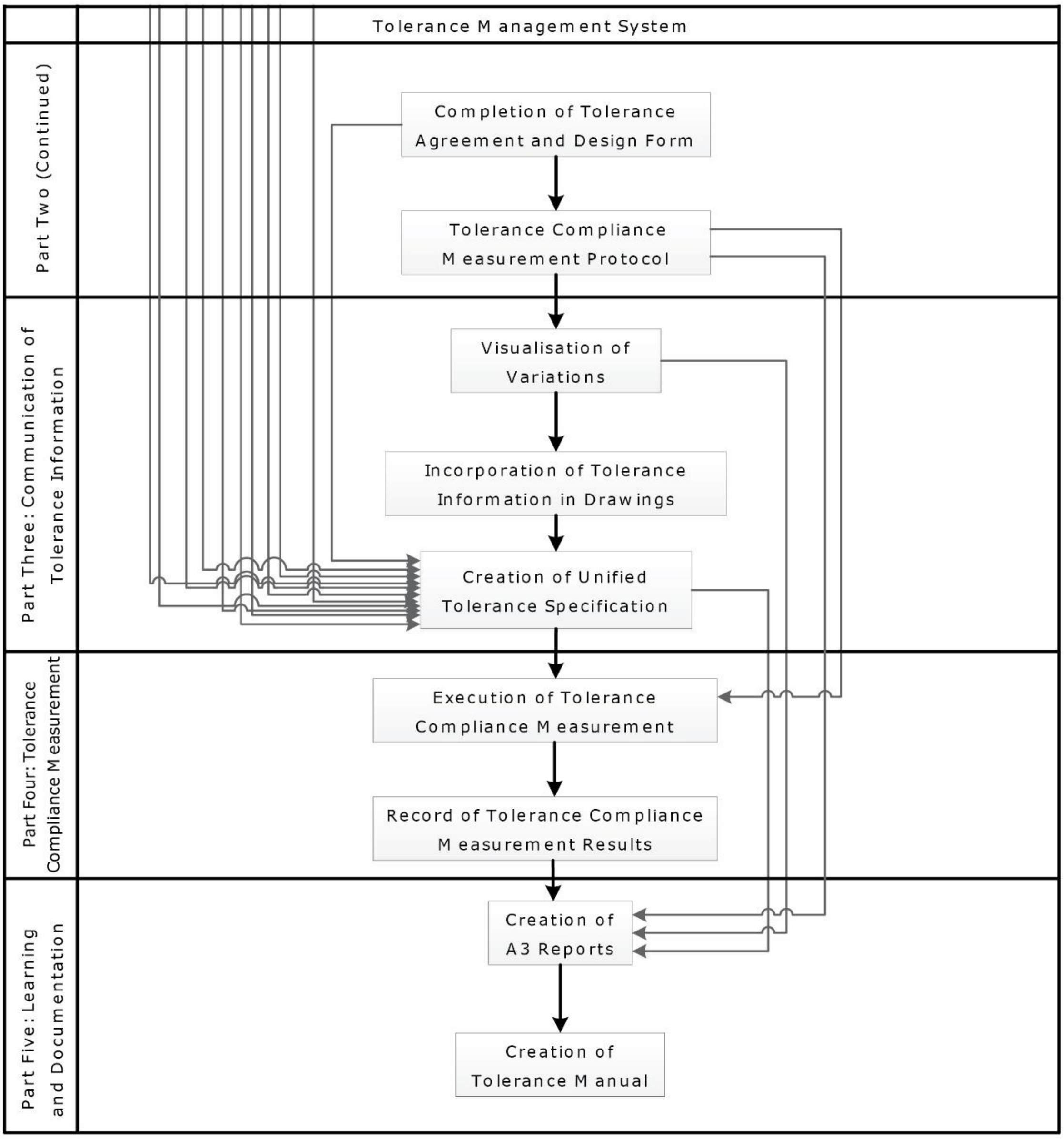



**Figure 6-70. Steps and flow of information between steps in Tolerance Management System**

## 6.3 Tolerance Management System: Organisational Design, Parts and Steps

In this section, first the organisational design in TMS and then the parts/steps of TMS are explained.

### 6.3.1 *Organisational Design in Tolerance Management System*

The organisational design proposed for TMS is presented in this section. The logic behind such a design is to combine the cross functional expertise within the project and the organisation (contractor), and benefit the most from their knowledge. It is envisaged that such an organisational design ensures that the involved parties have shared understanding about the key tolerance information (e.g. tolerance risks, critical dimensions, critical connections, and critical sub-assemblies) that are important for achieving tolerance requirements/mitigate tolerance risks. In other words, the aim is that functional groups do not work in isolation and are instead aware of the required accuracy of other groups and that their products or services are connected tolerance-wise. The organisational design includes the Tolerance Management Board, Tolerance Coordinator, and Tolerance Management Meetings.

#### 6.3.1.1 Appointment of the Tolerance Management Board

The Tolerance Management Board is expected to standardise and facilitate the dialogue regarding tolerances between the functional groups. The Tolerance Management Board is required because the conventional approach of inviting groups to the regular meetings (e.g. design review meetings, weekly meetings) and discussing tolerances among numerous other issues is likely to fail, according to the observations in cases one and two[3]. In essence, the Tolerance Management Board comprises of two committees, namely Strategic Tolerance Management (STM) Committee and Tactical Tolerance Management (TTM) Committee[4], which are explained next. Figure 6-71 represents the Tolerance Management Board.

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[3] This was explained in Sections 4.1.2.4 and 4.2.2.3.

[4] The idea of the proposing such an organisational design was inspired by the literature review in the manufacturing body of knowledge. This has been explained in Section 2.7.2.

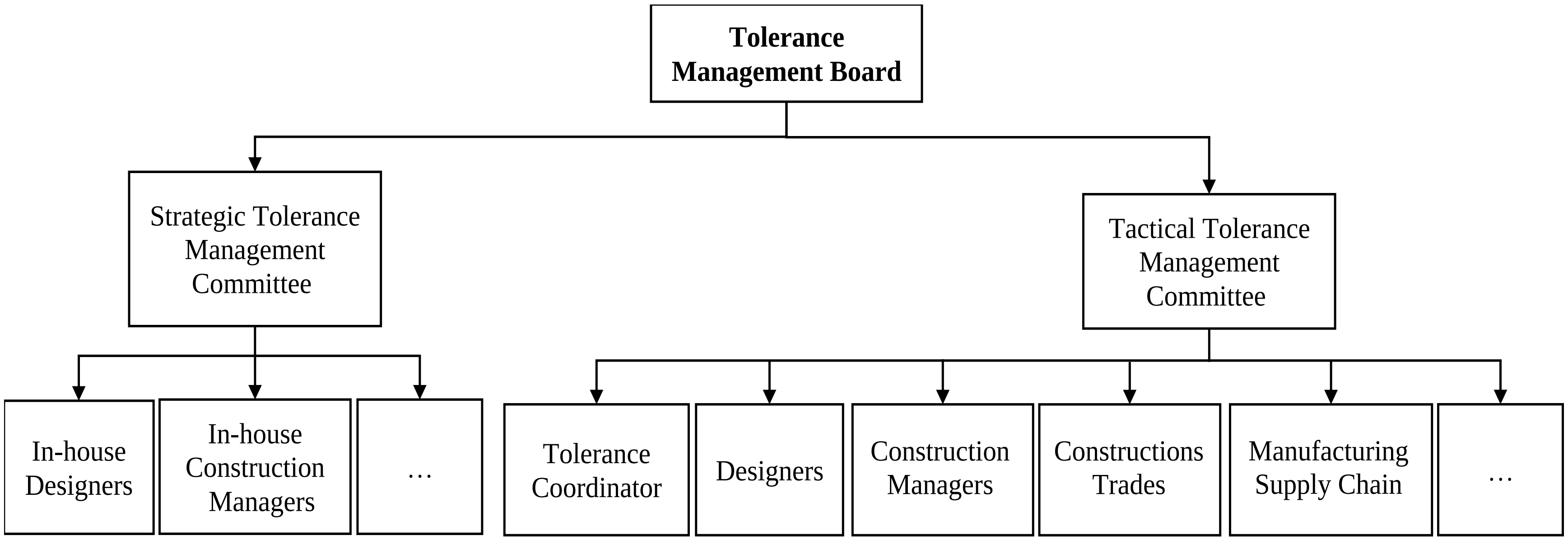



**Figure 6-71. Organisational design in Tolerance Management System**

#### *6.3.1.1.1Appointment of the Strategic Tolerance Management Committee*

The STM Committee acts at a company-wide level. Members of the STM Committee should include representatives from both the design and construction teams and members must be permanently based in the company, that is, they should be in-house. The Committee sets the company-wide policies regarding tolerance management and is not directly concerned with issues at the project level, unless at the TTM Committee's request.

The responsibility of the STM Committee is to:

- Maintain the decisions made and information collected at the tactical level and the results acquired after implementing TMS;
- Hand over relevant tolerance information to the TTM Committee at each stage of TMS;
- Maintain and update the Tolerance Manual (explained in Section 2.5);
- Resolve larger disputes between functional groups caused by tolerance problems.

#### *6.3.1.1.2Appointment of the Tactical Tolerance Management Committee*

The TTM Committee deals with the tolerance management at the project level based on the company-wide policies laid down by the STM Committee. Designers (e.g. architect, structural engineer) and construction trades (e.g. construction managers, subcontractors) are the key players at the tactical level of tolerance management. This is because designers and construction teams represent the two ends of the spectrum in the negotiations: designers are concerned about the aesthetic and serviceability of the final product and are as stringent as possible with tolerances, whereas construction teams are concerned about what economically is constructible, and desire tolerances to be as lenient as possible[5]. Ideally, the information found by the TTM committee should be armed with the information maintained by the STM Committee. The TTM Committee's responsibilities are defined as follows:

- Implement the steps of TMS;
- Refine the company-wide policy for tolerance management based on the characteristics of each project and recommendations in TMS;

[5] This has been explained in Section 2.4.

- Monitor the implementation of policies and ensure that all groups have comprehended the identified tolerance requirements and needed measures to achieve them;
- Issue instructions to obtain tolerance requirements and prevent/mitigate tolerance risks;
- Resolve disputes between groups when tolerance problems occur;
- Identify tolerance problems and investigate whose fault is and what the root cause is;
- Initiate discussions with those groups that are involved in tolerance problems;
- Specify realistic tolerance values for those components, for which tolerance values cannot be found in reference documents.

The TTM Committee has fixed members and rolling members. The former members are involved in the project from inception to the completion. Fixed members include Tolerance Coordinator, designers (architect, structural engineer), design managers, surveyors (quality control team), and construction manager[6]. The fixed members should participate in all TMMs. The responsibilities of the fixed members are explained in Table 6-31. The TTM Committee should invite rolling members when investigating tolerance issues particularly relevant to them. The rolling members include designers, construction trades and manufacturing supply chain. If the TTM Committee needs more clarification from the client, the representative of the client should join the TTM Committee as a rolling member.

[6] American Concrete Institute (2004) suggests that architect, engineer, general contractor, and construction manager should attend tolerance coordination meetings. During the empirical studies one and two, it was observed that design managers and surveyors play an important role in the tolerance coordination. Therefore, the list was suggested for the fixed members of the TTM Committee.

**Table 6-31. Responsibilities of the fixed members of the TTM Committee**

| FIXED MEMBERS | RESPONSIBILITIES OF THE FIXED MEMBERS |
|---|---|
| Designers | The role of the designers is highlighted particularly at the early stages of design. They are responsible for working with each other and also with the construction and manufacturing trades to minimise the negative impacts of deviations by deploying appropriate measures in design. |
| Manufacturing supply chain | Given several components are supplied by outside vendors and those components often have a remarkably higher accuracy compared to *in situ* components, the manufacturing supply chain has a significant impact on the quality of sub-assemblies. That is, when tolerance requirements/risks are identified, the focus should be on the areas where there is a connection with *in situ* components. The manufactured components often should either absorb or block out the variations of the *in situ* components. |
| Surveyor | Surveyors are often familiar with the areas where tolerance issues may arise and how they should be overcome. Also, their input is needed to determine how the identified tolerance requirements can be controlled during construction. |
| Commercial Manager | Commercial Managers should evaluate the costs of the desired accuracy, mitigation strategies, modification of tolerance problems, and help the committee to make more cost effective decisions. |
| Design Manager | Design Managers should ensure that designs fit together by accounting for tolerances. |

#### 6.3.1.2 Appointment of the Tolerance Coordinator

There is a need to introduce a new role in order to reinforce the successful implementation of TMS, especially because the moderation of discussions made in the TTM Committee and communication between the Tactical and Strategic Tolerance Management Committees requires a new role. The new role is called the Tolerance Coordinator[7] and it can be either a separate role or it can be added to one of the existing roles.

The Tolerance Coordinator is a neutral member of the TTM Committee, particularly between the two extremes of the design disciplines and the construction trades. The Tolerance Coordinator should hold a trade-off between the requirements raised by all the participants.

It is important that the Tolerance Coordinator has a general understanding of various fields of knowledge related to tolerances, including the different types of connections, common tolerance problems, tolerance analysis methods, and methods for tolerance compliance measurement. If the appointed Tolerance Coordinator is not treated as

[7] The idea of Tolerance Coordinator was inspired during the interview with an academic experienced in the field of tolerance management. Also, it is suggested by American Concrete Institute (2014).

an independent role in a project, then it would be most beneficial to merge this role with that of the architect, site engineer or design manager[8].

The Tolerance Coordinator is responsible for ensuring that tolerance risks are proactively identified and appropriate resolutions are developed to either eliminate sources of tolerance risks or to reduce the impacts of such risks. The person who is assigned to this role should be concerned with tolerances from the concept design stage through to the completion of the construction. Particularly during the design stage, the Tolerance Coordinator should make sure that the design produced is economically constructible on site[9]. More specifically, the Tolerance Coordinator has the overall responsibility to implement TMS throughout the design and construction by:

- **Adopting** suitable steps from TMS based on project sensitivity and complexity. (Following all the steps of TMS may not be necessary for projects with less complexity[10]);
- **Monitoring** the consistency of the communication and collaboration between the project team to ensure the full application of TMS;
- **Capturing** the necessary tolerance information and agreements;
- **Examining** the correctness and validity of the tolerance information, agreements, and decisions;
- **Performing** the required tolerance analysis.

#### 6.3.1.3 Tolerance Management Meetings

The Tolerance Management Meetings (TMMs)[11] offer a forum for the TTM Committee, whereby members can open a dialogue specifically about tolerances based on both common and competing interests. Note that the difference between the TMMs and other types of meetings (e.g. design review meetings) is that the TMMs are purely about tolerances. TMMs are essential because tolerance issues can have severe

[8] During the empirical studies, it was found that these three roles have the best understanding of tolerance management. The literature mainly considers architect responsible for tolerance coordination (explained in Section 2.4).

[9] It was explained in Section 2.2 that the main purpose of tolerance coordination is to ensure that designs are constructible.

[10] One of the shortcomings of TMS at the moment is that it does not state what steps must be followed for each project with a certain level of complexity. As a result, TMS for typical projects might seem onerous.

[11] The idea of Tolerance Management Meetings was inspired by American Concrete Institute (2014), as explained in Section 2.4.1 and Appendix D.

consequences particularly in complex projects. However, in projects with less complexity, it is suggested to hold TMMs as part of other regular meetings.

TMMs should be held at three stages of a project: prior to bidding, pre-construction, and construction. Those types of meetings are explained individually as follows:

- **Pre-bid TMMs**: The pre-bid TMMs should be held after the client's brief has been received and the concept design is generated, and before subcontractors and suppliers are procured. The pre-bid TMMs is a forum where bidders can discuss whether they have fully perceived the tolerance requirements/risks raised by the TTM Committee up to that point of the project. This will help the bidders to bid in proportion to actions needed to satisfy the tolerance requirements. The pre-bid TMMs are envisioned to be of great benefit to the general contractor and client because the work will be completed with a lesser risk of disputes and a lower probability of the need to change the design and take other measures (e.g. apply for contingency funds due to tolerance risks or problems);
- **Pre-construction TMMs**: The pre-construction TMMs should provide the potential opportunity for all functional groups to determine tolerance requirements/risks at the pre-construction stage, who can then make realistic and collective decisions about the assembly process, types of materials and components, types of connections, component tolerances, sub-assembly tolerances, tolerance compliance measurements, and all other important topics indicated in TMS;
- **Construction TMMs**: The construction TTMs are held during the construction process and allow the TTM Committee to implement TMS, particularly with a larger number of rolling members. Such meetings are useful to resolve tolerance problems and mediate disputes.

### *6.3.2 Part One: Identification of Tolerance Requirements / Risks*

#### 6.3.2.1 Identification of the Key Information in the client's Brief and Concept Design

The TTM Committee should look for the information listed in Table 6-32 throughout the client's brief and in the concept design. Finding this information is the starting point to perceive the tolerance requirements/risks in a building. The client's brief may be in the form of generic and nontechnical descriptions. In the next steps, the information should be translated into a standard language used in TMS. The information should be fully captured by the TTM Committee, especially in pre-bid and pre-construction TMMS, before proceeding to the next steps. It is essential to fully capture the key tolerance information outlined in the client's brief because: (a) contractors can bid on the project accordingly to avoid inconsistency between the required level of accuracy and the allocated budget, and (b) when they will be let the project, they will take appropriate actions explained in next steps to meet the requirements.

**Table 6-32. Key information in the Client's brief and the reasons why such information is required**

| KEY INFORMATION | REASON FOR REQUIREMENT |
|---|---|
| The information regarding: (a) tolerance values on materials and components (e.g. flatness of concrete slabs), (b) construction/fabrication/manufacturing tolerances, (c) permissible limits for building movement, and (d) construction methods to achieve the required level of accuracy (e.g. use of movement joints, use of precast concrete slabs) outlined in the Client's brief. | It is important to know the required tolerance values on materials and components, and the permissible sources of variations (i.e. construction/ fabrication/ manufacturing, building movement) before selecting those materials and components and selecting a work method to assemble/construct them (explained in Section 2.3.1). If a particular work method is suggested to achieve tolerance requirements, it should be taken into account. |
| Construction type (i.e. traditional or skeletal frame) | Each construction type has its own structural behavior (Curtin, Shaw, Parkinson, Golding, & Seward, 2008), and also varying fabrication/erection tolerances (British Standards Institution, 1990).<br>Each construction type has a different weight (i.e. different construction methods result in different amounts of dead loads). Weight is important to calculate dead loads applied to the building (Curtin et al., 2008). |
| Structural form (e.g. concrete, steel) | Like the construction type, different structural forms have different structural behaviours and their fabrication/erection tolerances vary. For example, concrete structures normally have less deflection compared to steel structures(Curtin et al., 2008). |
| Construction method (e.g. *in-situ*, prefabrication, precast) | The accuracy of factory-made components is often higher than that of *in situ* components (explained in Section 2.4). |

**Table 6-32 Continued**

| KEY INFORMATION | REASON FOR REQUIREMENT |
|---|---|
| Building envelope (e.g. cavity wall, glazed brick, precast cladding, stone cladding, wood cladding, glass block, glazed concrete block) and fenestration (e.g. sash, casement, jalousie, clerestory, skylight, Diocletian window, French window, bay window, multi-lit widow) | The sensitivity of different types of envelopes to the variation of the building structure is different. For example, glass is brittle and extra care should be taken when glazed components are put next to the building structure which is subject to movement (according to interviews in case three).<br>The ways induced and inherent variations are accommodated at the connections between the envelope/fenestration and structure vary. In other words, the provision of appropriate connections, if possible at all, varies in each type of the building envelope/fenestration (explained in Section 2.11). |
| Shape of the building | Tolerance risks in buildings with complex shapes (e.g. curvy shapes, special aesthetical elements attached to the exterior) are higher (Birkeland & Westhoff, 1971) (like case one, which had curvy shape and fins were attached to the building envelop and as a result, tolerance problems occurred-explained in Section 4.1.3.10). |
| Floor finishes (e.g. stone, concrete, ceramic tiling, terrazzo tiling, etc.) | The installation of floor finishes requires different levels of flatness of the surfaces (American Concrete Institute, 1989). Note that if concrete is the final finish, the flatness is of a prime importance (like case one in which concrete was the final finish but because the required level of flatness was not achieved, the design had to change-explained in Section 4.1.3.2) |
| Spatial constraints | Depending on the type of construction, the internal area and volume (e.g. in office development), the flatness of surfaces, etc., can be of a prime importance (according to interviews in case three). For example, the flatness in warehouses is important (Concrete Society Party, 2003) |

### 6.3.2.2 Determination of Maximum Loads Acting on the Structure and General Deflection Criteria

The TTM Committee and, more specifically, the structural engineers should provide an overview of the loads that will be applied to the building due to the weight of the structural and non-structural members, and the resultant building movement. This will help the general contractor to choose subcontractors whose systems are compatible with the potential movement. The loading and movement of the structure are anticipated based on the information found in the client's brief and concept design.

#### 6.3.2.3 Selection of Classes of Tolerances

It is important to determine the class of tolerances because choosing more stringent tolerances rather than tolerances of a normal class has cost implications. Hence, the class of tolerances should be decided by the TTM Committee before the tender stage. Note that unless otherwise requested from the TTM Committee, subcontractors automatically assume that only the normal class of tolerances is requested and they bid for this class.

Moreover, the selection of a class of tolerance can introduce a new risk to the project. This is because it can either be difficult for the construction trades to achieve that class of tolerance or it may be the case that obtaining that class of tolerance exceeds the construction trades' capabilities. For example, assume that the TTM Committee selects the particular class of tolerance for columns interfacing with the cladding system in a ten storey building. The committee allocates only ±10 mm for plumbness of those columns, whereas normal classes of tolerances outlined in (British Constructional Steelwork Association, 2010) means that columns can be out of plumb by nearly 40 mm. Accordingly, a cladding system is supplied that can absorb only 10 mm deviations of the columns. In this scenario, there is a tolerance risk that the particular desired class of tolerance for columns may not be achievable, even though the subcontractor accepts to make it at a higher cost.

Arguably, the geometric accuracy of buildings (i.e. accuracy in form), to a great extent, is governed by the perpendicularity and position of the columns, level of beams, and flatness of surfaces[12]. It would be costly to apply the special class of tolerances to the entire structure. Hence, it seems sensible if particular tolerances are applied where structural members are connected to the non-structural members (e.g. internal partitions or building envelope) and tolerance risks are conceivable.

Table 6-33 includes the categorisation of classes of tolerances, their definitions, their applications, and examples of possible applications of each class of tolerance[13].

[12] This was implied in Section 4.3, was mentioned by two of interviewees in case one, and was observed in ten out of fifteen tolerance problems identified during the empirical studies.

[13] This was explained in Section 2.3.3.

**Table 6-33. Classes of tolerances and the corresponding definitions, applications and examples of the applications**

| CLASSES OF TOLERANCES | DEFINITIONS | APPLICATIONS | EXAMPLES OF THE MOST COMMON APPLICATIONS |
|---|---|---|---|
| Normal tolerances[1] | They include normal tolerances. | They are necessary for all types of buildings. | Typical buildings |
| Particular tolerances[2] | They include more stringent tolerances than normal tolerances. | They are only applied to certain components or certain dimensions. | Perpendicularity of the columns bounding the lift shaft.<br>Perpendicularity of the external columns, especially in tall multi-story buildings to avoid: (a) fit-up problems with cladding, and (b) problems with site boundaries or building lines (Davison & Owens, 2012).<br>Slab thickness in the construction of steel decking/ composite concrete suspended slabs as the permitted tolerances are often not met (CONSTRUCT Concrete Structure Group, 2010) |
| Special tolerances[3] | They include more stringent tolerances than normal tolerances | They are applied to an entire structure or project. | Special structures such as nuclear reactors and containment vessels, pre-stressed circular structures, and highly geometric structures. |

[1] They are also known as 'essential' tolerances for the steel and 'class 1' for concrete.

[2] They are also known as 'functional' tolerances for the steel and 'class 2' for concrete.

[3] The term 'special tolerance' has not been used for the concrete but, presumably, it can be used for concrete too.

#### 6.3.2.4 Identification of Critical Connections and their Associated Risk Using Tolerance Interdependency Matrix

Buildings are assemblies made up from several interacting components. Dimensional and geometric (i.e. form, position and orientation tolerances) accuracy of each component often depends on many variables, including the dimensional and geometric accuracy of other components. For example, when concrete slabs deflect, it may not be possible (or extremely difficult) to install the internal partition walls vertically with the desired tolerance. However, given the fragmented nature of construction, each component is often designed and constructed by an individual functional team in isolation. The challenge is to integrate the tolerance-wise interdependent functional groups during the design and construction to proactively recognise the tolerance requirements/risks and cope with them.

To capture the interdependency of components tolerance-wise, a matrix comprising a list of components is created. The matrix is named Tolerance Interdependency

Matrix[14]. Components used in projects are listed both in the rows and columns of the matrix. The row represents the succeeding components and the column represents the preceding components (Table 6-34). For clarification, the column illustrates the components that have been installed first and the row illustrates the components next to or on the top of the preceding components (i.e. components that have been installed after). If there is any physical connection (i.e. joint or interface) between the componenti ($C_i$) and componentj ($C_j$), the interrelated cell is filled with 1; otherwise, it is filled with 0. The matrix is not symmetric because the sequence of installation/erection of component is recorded. Equation 1 summarises the instruction to complete the matrix.

$$\text{Equation 1. } \forall_{x,y}: \begin{cases} e_{x,y} = 1, & If\ C_i\ affects\ C_j\ tolerance\ wise \\ e_{x,y} = 0, & Otherwise \end{cases}$$

**Table 6-34. Example of the Tolerance Interdependency Matrix**

| | | SUCCEEDING COMPONENTS | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | $C_1$ | $C_2$ | $C_3$ | $C_4$ | $C_5$ | $C_6$ | $C_7$ | $C_8$ | $C_9$ | $C_{10}$ |
| PRECEDING COMPONENTS | $C_1$ | -- | 1 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 |
| | $C_2$ | 0 | -- | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 |
| | $C_3$ | 0 | 1 | -- | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | $C_4$ | 1 | 0 | 0 | -- | 1 | 0 | 0 | 1 | 0 | 0 |
| | $C_5$ | 0 | 0 | 0 | 0 | -- | 0 | 1 | 0 | 0 | 0 |
| | $C_6$ | 0 | 0 | 1 | 1 | 0 | -- | 0 | 0 | 1 | 0 |
| | $C_7$ | 0 | 0 | 0 | 0 | 0 | 0 | -- | 1 | 1 | 0 |
| | $C_8$ | 0 | 1 | 0 | 0 | 0 | 0 | 0 | -- | 0 | 0 |
| | $C_9$ | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | -- | 0 |
| | $C_{10}$ | 1 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | -- |

Once the matrix has been completed with information and the physical connections have been identified (i.e. interdependency of components tolerance-wise), the cells should be coloured based upon the associated risks of connections. The associated risk for each connection is defined by: (a) the collective decision of the TTM

[14] The idea of the Tolerance Interdependency Matrix originally comes from the 'Design matrix of auto mode' developed by Suh (2001). This matrix was not explained in the Literature Review Chapter because this matrix is not directly used for tolerances, and because of the word limits. Moreover, the Project Director of the case one during an interview urges a need to having a method through which connections can be identified. All in all, the author developed this matrix to be used in TMS.

Committee, and (b) predetermined risk of connections in TMS. Note that the committee should account for the classes of tolerances, identified in the previous step, when determining the risk of each connection.

Table 6-35 lists the pre-determined risk of connections[15]. The basis of this categorisation is remedial costs, functionality of sub-assemblies, and safety limits. The red colour illustrates the sub-assemblies with extreme and high tolerance risk, the orange colour illustrates medium tolerance risk, and the green colour illustrates low tolerance risk. These three levels of risks are defined below:

- **The medium risk connections**: The remedial costs are lower, the functionality is adversely affected but the functionality of the connection still conforms to the specifications[16];
- **The high risk connection**: The remedial costs are higher, the functionality is adversely affected in such a way that the connection does not work as intended[17];
- **The extreme risk connection**: The remedial loss costs are highest and the risk concerns the safety of users[18].

[15] Table 6-35 was developed based on the information given in (British Standards Institution, 1990) (explained in section 2.7.3.3), and also from the understanding gained after analysing the identified tolerance problems in cases one and two.

[16] For example, in case two, there was a connection between the structure and cladding. It transpired that some columns were out of plumb but the problem was not observed when fitting the cladding panels. Hence, this connection is assumed to be a medium risk connection.

[17] For example, in case two, doors could not be fitted in the doorways because the rows of columns, PFCs, and cladding rails were not aligned, but there was no concern regarding the safety of the doors. Hence, the connection between the doors and structure is assumed to be a high risk connection.

[18] For example, in case one, the steel beam was deflecting more than anticipated initially and there was a risk that the stone panels would fall off over time and there was therefore a concern regarding the safety of the people walking around the building. Hence, the connection between the structure and cladding was an extreme risk connection.

**Table 6-35. Type of connections, their associated risk, and examples**

| TYPE OF CONNECTIONS | RISK | EXAMPLE |
|---|---|---|
| Connections between members of the structural frame and the envelope/fenestration | Extreme | Steel/concrete frame to the glazed curtain walling |
| Connections between the structural frame and the lift well | Extreme | Slab edge to lift well and lift doors |
| Connections between the members of the frame and doors, panelling units and prefabricated partitions | High | Concrete slab to partition walls with recessed skirting |
| Connections between the structural frame and the stairwell | High | |
| Connections between the structure and the pipework | High | Inlets/outlets for pipework and conduit connected to the structure |
| Connections between the structure and the ductwork | High | Ventilation grilles to the structural openings |
| Connections between other components inside the building | Low / Medium | Door frame between partition walls |

Table 6-36 shows the filled Tolerance Interdependency Matrix for case one. The matrix comprises of 17 components and their interdependencies tolerance-wise are demonstrated. The associated risk of connections is recognised using Table 6-35.

After the Tolerance Interdependency Matrix is populated by the TTM Committee, it should be passed to the tendering team. The matrix is an important means to identify connections with high risk during the tendering process, especially in projects with a compressed schedule. This will help the tender team to procure functional groups responsible for components in the critical connections.

**Table 6-36. Completed Tolerance Interdependency Matrix for case one**

| | | | SUCCEEDING COMPONENTS | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | FOUNDATIONS | CONCRETE SLABS | STEELWORK | CEILINGS | ROOF | STAIRCASE | CURTAIN WALL | WINDOWS | BALUSTRADE | PARAPETS | FINS | INTERNAL PARTITIONS | JOINERY | LIFT WELL | FLOORING | HVAC | STONE CLADDING |
| | | | $C_1$ | $C_2$ | $C_3$ | $C_4$ | $C_5$ | $C_6$ | $C_7$ | $C_8$ | $C_9$ | $C_{10}$ | $C_{11}$ | $C_{12}$ | $C_{13}$ | $C_{14}$ | $C_{15}$ | $C_{16}$ | $C_{17}$ |
| PRECEDING COMPONENTS | FOUNDATIONS | $C_1$ | 0 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | SLABS | $C_2$ | 0 | 0 | 0 | 1 | 1 | 1 | 1 | 0 | 1 | 0 | 0 | 1 | 1 | 0 | 1 | 0 | 0 |
| | STEELWORK | $C_3$ | 0 | 1 | 0 | 1 | 1 | 1 | 1 | 1 | 0 | 0 | 1 | 0 | 0 | 1 | 0 | 1 | 1 |
| | CEILING | $C_4$ | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 1 | 0 |
| | ROOF | $C_5$ | 0 | 0 | 0 | 1 | 0 | 1 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | STAIRCASE | $C_6$ | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | |
| | CURTAIN WALL | $C_7$ | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | WINDOWS | $C_8$ | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | BALUSTRADES | $C_9$ | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | PARAPETS | $C_{10}$ | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | FINS | $C_{11}$ | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | PARTITIONS | $C_{12}$ | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 |
| | JOINERY | $C_{13}$ | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | LIFT WELL | $C_{14}$ | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 |
| | FLOORING | $C_{15}$ | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 0 | 0 | 0 | 0 |
| | HVAC | $C_{16}$ | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | CLADDING | $C_{17}$ | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

### 6.3.2.5 Identification of Critical Sub-Assemblies Using Tolerance Interdependency Network

A building, as an assembly, comprises of several sub-assemblies. Sub-assemblies are created by two or more components, the dimensional and geometric accuracy of which are interdependent[19]. In a sub-assembly, the probability of tolerance risks can be high when trying to fit a component within the already installed components. This is because its fit or lack of fit highly depends on the accuracy of the already installed components. For an example, when installing curtain walls, fit or lack of fit of the curtain walls depends on the position tolerance and deflection limits of the beams, and also the position tolerances and plumbness tolerances of columns in a frame (explained in Section 4.4.1.6). Therefore, the risk of tolerance problems does not only depend on one single component but also its predecessors/successors in a sub-assembly. In other words, the success of a sub-assembly depends on the success of all the components creating that sub-assembly. The goal behind the identification of sub-assemblies is to examine the dimensional and geometric relationship between components creating a sub-assembly and then to design each component accordingly.

The TTM Committee can recognise the sub-assemblies by using the findings (i.e. connections) from the Tolerance Interdependency Matrix and deploying a technique called Tolerance Interdependency Network[20] (TIN). TIN is explained through the following example. From Table 6-34, it can be perceived that $C_4$ is interdependent with $C_1$, $C_5$ and $C_8$. Moreover, $C_1$ is interdependent with $C_5$. TIN is used to illustrate the interdependencies between those components better and to identify sub-assemblies. First, the acronym of the component in question is written. Then the acronyms of other components, which are interdependent tolerance-wise to the main component, are written. Afterwards, arrows should connect the interdependent components. As an agreement, in TIN, the starting point of an arrow is the proceeding component and the end point of the arrow is the succeeding component. In Figure 6-72, it is shown that $C_4$ is interdependent tolerance-wise with $C_1$, $C_5$ and $C_8$ by

[19] Note connection is a sub-assembly but sub-assembly is a more generic term to describe the situation when more than two components are interdependent tolerance-wise (explained in Section 2.2).

[20] The idea of Tolerance Interdependency Network was inspired from a presentation by Professor Daniel E. Whitney during the Robust Design Day symposium 2016 at the Technical University of Denmark. Professor Whitney presented the 'Network Model of Bicycle' through which he identified the communities developing a bicycle. Given the word limits and also the application of this technique for other field of research and not tolerances, this technique was not presented in Chapter 2.

connecting $C_4$ to those components using an arrow. There is also an arrow connecting $C_1$ to $C_5$, which means these two components are interdependent as well. In Figure 6-72, it is shown that $C_4$, $C_1$, and $C_5$ create a sub-assembly. The arrows demonstrate that the assembly sequence is $C_4$, $C_1$ and then $C_5$. This is because $C_4$ is the predecessor of $C_1$ and $C_5$, and $C_1$ is the processor of $C_5$. Using TIN helps the TTM Committee to find the sub-assemblies easier. It is suggested that the interdependencies would be visualised for each component separately. The component in question as part of TIN is named the centric component (in Figure 6-72, it is $C_4$). This technique is meant to replace the conventional method in which components are designed regardless of other components.

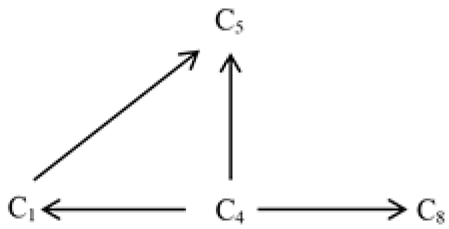



**Figure 6-72. Tolerance Interdependency Network based on findings from Table 6-34 while C4 is the centric component**

To illustrate the point further, the sub-assemblies in case one are identified using the findings from the completed Tolerance Interdependency Matrix (Table 6-36) and deploying TIN. The TINs and corresponding sub-assemblies are presented in Table 6-37.

**Table 6-37. List of TINs for case one and corresponding sub-assembly or sub-assemblies**

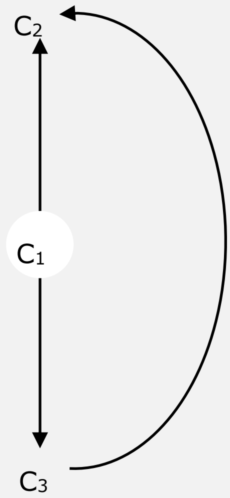
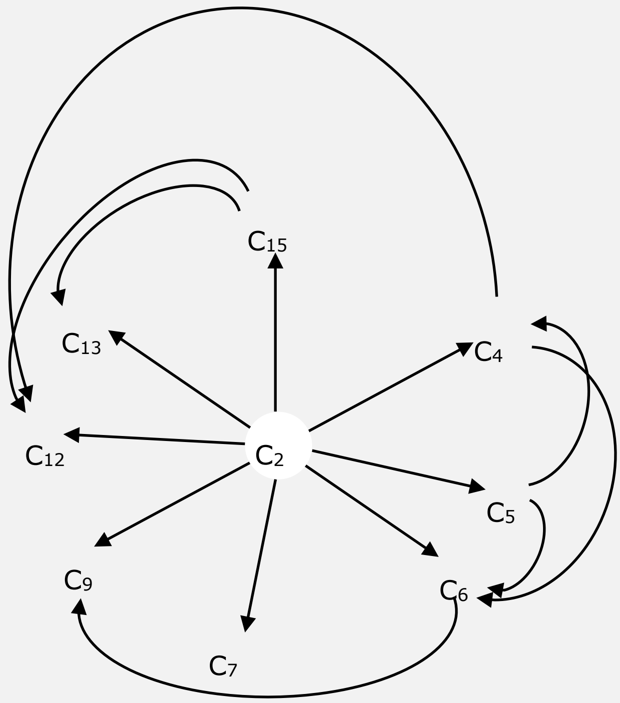
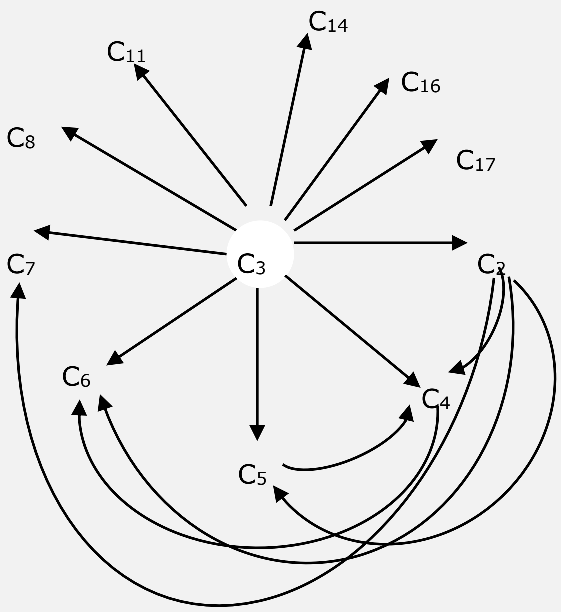
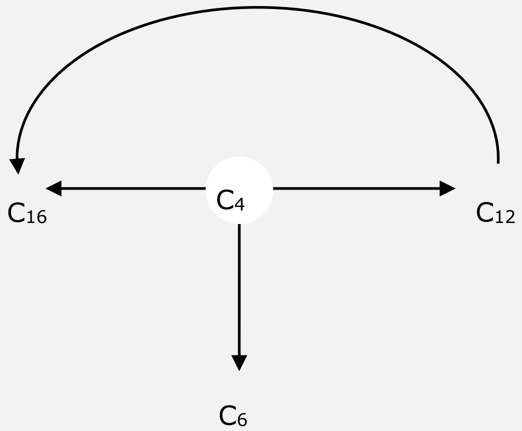
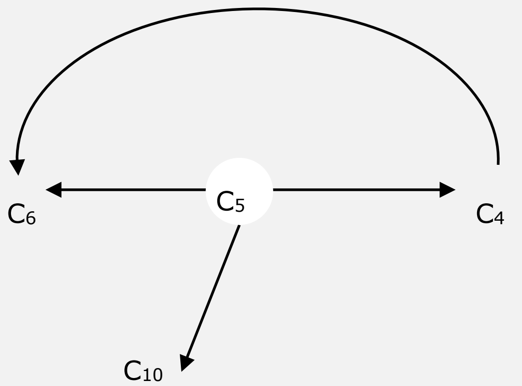
<table>
<tr><th>CENTRIC COMPONENT</th><th>TOLERANCE INTERDEPENDENCY NETWORK (TIN)</th><th>IDENTIFIED SUB-ASSEMBLY OR SUB-ASSEMBLIES</th></tr>
<tr><td>Foundations ($C_1$)</td><td>
</td><td>Foundations ($C_1$), steelwork ($C_3$), concrete slabs ($C_2$)</td></tr>
<tr><td>Concrete slabs ($C_2$)</td><td>
</td><td>Concrete slabs ($C_2$), roof ($C_5$), ceiling ($C_4$), stairwell ($C_6$)<br>Concrete slabs ($C_2$), ceiling ($C_4$), internal partitions ($C_{12}$)<br>Concrete slabs ($C_2$), stairwell ($C_6$), balustrades ($C_9$)<br>Concrete slabs ($C_2$), flooring ($C_{15}$), internal partitions ($C_{12}$), joinery ($C_{13}$)</td></tr>
</table>

**Table 6-37 Continued**

| CENTRIC COMPONENT | TOLERANCE INTERDEPENDENCY NETWORK (TIN) | IDENTIFIED SUB-ASSEMBLY OR SUB-ASSEMBLIES |
|---|---|---|
| Steelwork ($C_3$) |  | Steelwork ($C_3$), concrete slabs ($C_2$), roof ($C_5$), ceiling ($C_4$), stairwell ($C_6$), curtain wall ($C_7$)<br>Steelwork ($C_3$), ceiling ($C_4$), staircase ($C_6$)<br>Steelwork ($C_3$), roof ($C_5$), ceiling ($C_4$) |
| Ceiling ($C_4$) |  | Ceiling ($C_4$), internal partitions ($C_{12}$), HVAC ($C_{16}$) |
| Roof ($C_5$) |  | Roof ($C_5$), ceiling ($C_4$), stairwell ($C_6$) |

One may argue that the identified sub-assemblies are not of equal importance. The decision of which sub-assemblies are critical and should be analysed more carefully lies with the TTM Committee.

#### 6.3.2.6 Identification of Key Characteristics of the Components/Sub-Assemblies

Key Characteristic (KC) in TMS is a feature of a component or a sub-assembly that is sensitive to variation (explained in Section 2.12.2). A feature is categorised as a KC when its variation from the target value can result in: (a) costly remedial actions, (b) damage to the functionality, or (c) lack of safety of the building. Moreover, a feature can be a KC only when its variation is likely to occur. Many features are conceivable in a component or sub-assembly. For instance, the flatness of concrete surfaces in foundation is a feature. However, it is not a KC, because:

- Variation in flatness of concrete surfaces of foundation is not important. That is why the tolerance specified for them is already lenient;
- The target tolerance for the flatness of those surfaces is easily achievable and it is unlikely that the final flatness of surfaces would exceed the specified tolerance;
- Even if the final flatness of those surfaces does not adhere with the specified limits, it is unlikely that: (a) there would be a need for costly remedial actions, (b) the functionality of the foundation would be affected, or (c) the safety of the building would be threatened.

KCs on components and sub-assemblies should be recognised. The goal of the identification of KCs is to create a holistic view of how quality in the context of tolerance management is delivered (i.e. how the desired accuracy is achieved without any tolerance problems). Once KCs on components and sub-assemblies are known, the TTM Committee can focus on KCs only when assigning tolerances in the next steps of TMS, hence, this strategy (i.e. identification of KCs and only focusing on them) is expected to be more cost and time-effective. Tolerances of features that are not KC can be adopted from reference documents if necessary.

The types of KCs on a component or sub-assembly are divided into six categories shown in Table 6-38. The categorisation has been explained in Section 2.12. Such categorisation is expected to help the TTM Committee to identify KCs systematically.

**Table 6-38. List of Key Characteristics and the corresponding definitions and examples**

| TYPES OF KEY CHARACTERISTICS | DEFINITIONS | EXAMPLES |
|---|---|---|
| Straightness | This feature is related to the amount of variation caused by deformation and it is defined as the amount of variation of each line element of a component when subject to loads. These deformations include beam deflection and column buckling. | Deflection of an edge concrete beam. |
| Flatness | This feature is about the deviation in flatness that a surface may have. | Flatness of concrete slabs. |
| Parallelism | This feature is about the amount of deviation that a component may have from being parallel to another component. | The parallelism of stanchions to ensure that electrically operated shutter doors will fit in the doorways (like the tolerance problem one in case two-explained in Section 4.2.3.1). |
| Perpendicularity | This feature is about the amount of variation that a component may have from being perpendicular to a surface or another component. | Plumbness of columns to ensure the fit, functionality and aesthetic of the interfacing cladding system. |
| Position | This feature is about the amount of variation that the position of a component may have from the target (i.e. perfect) position (e.g. position of the base plates). | Position of columns, base plates and other components. |
| Critical dimension | Dimensions that affect the functionality of a component or sub-assembly more than other dimensions are termed critical dimension. | Clearance needed between components<br>Floor thickness (i.e. thickness of the floors falls under the category of critical dimensions). It should be investigated whether tolerances for the floor thickness impact inserts and embeds (American Concrete Institute, 2014) |

For critical dimensions, more extensive examples are given in Appendix K.

#### 6.3.2.7 Tolerance Risk Assessment (Part One)

The tolerance risk assessment is defined as a systematic process for risk identification, risk analysis, and the generation of strategic responses to tolerance risks. This is to ensure that tolerance requirements in the project are met. Tolerance risk assessment is an integral step of TMS. The objective of this step is to: (a) develop a standard and consistent approach for identification, classification, assessment, analyses and action planning of tolerance risks, (b) to help the TTM Committee to balance the design intents against potential risks, and (c) to develop a consistent language that is able to establish a shared understanding of tolerance risks among the project participants.

The tolerance risk assessment is gradually progressing and is iterative. This is because there is always a possibility that new risks are identified as the project moves forward, more parties become involved and designs evolve. In other words, as the TMM Committee gathers more information, more tolerance risks may be identified. In essence, the process of the identification of tolerance risks to some extent is subjective. The decisions made in this step are influenced by the desire to avoid monetary loss, delay, and poor quality due to tolerance problems and are based on previous experiences of the TMM Committee.

The defined judgmental and heuristic rules in the tolerance risk assessment aim to reduce the uncertainty and vagueness shrouded in typical risk assessments. The hierarchical risk breakdown structure (HRBS) is used for the tolerance risk assessment (explained in Section 2.7.3). The HRBS divides risks into two categories: internal and external. Internal risks are related to the management of resources involved in the project and external risks are related to resources prevalent in the external environment that dominate the internal resources. In other words, the internal tolerance risks originate from the project members, whereas the external risks are imposed to the project members. General contractors have control over the internal risks but they have less control over the external risks. Given the uncontrollable nature of external risks, these types of risks should be continuously monitored and appropriate countermeasures should be taken to deal with them.

The root causes of tolerance problems (explained in Chapter 5) are the basis risk factors, shown in Figure 6-73. Such risk factors do not directly result in tolerance problems but they do lead to specific risks if they are not prevented/mitigated properly. In other words, tolerance risks are triggered by risk factors which are identified as root causes of tolerance problems. The risk factors (i.e. root causes) of tolerance risks are: Organisation, Tolerance Specification/Tolerances in Specifications, Work Method/Workmanship, Quality Control Systems, Regulations, Special Causes, and Training.

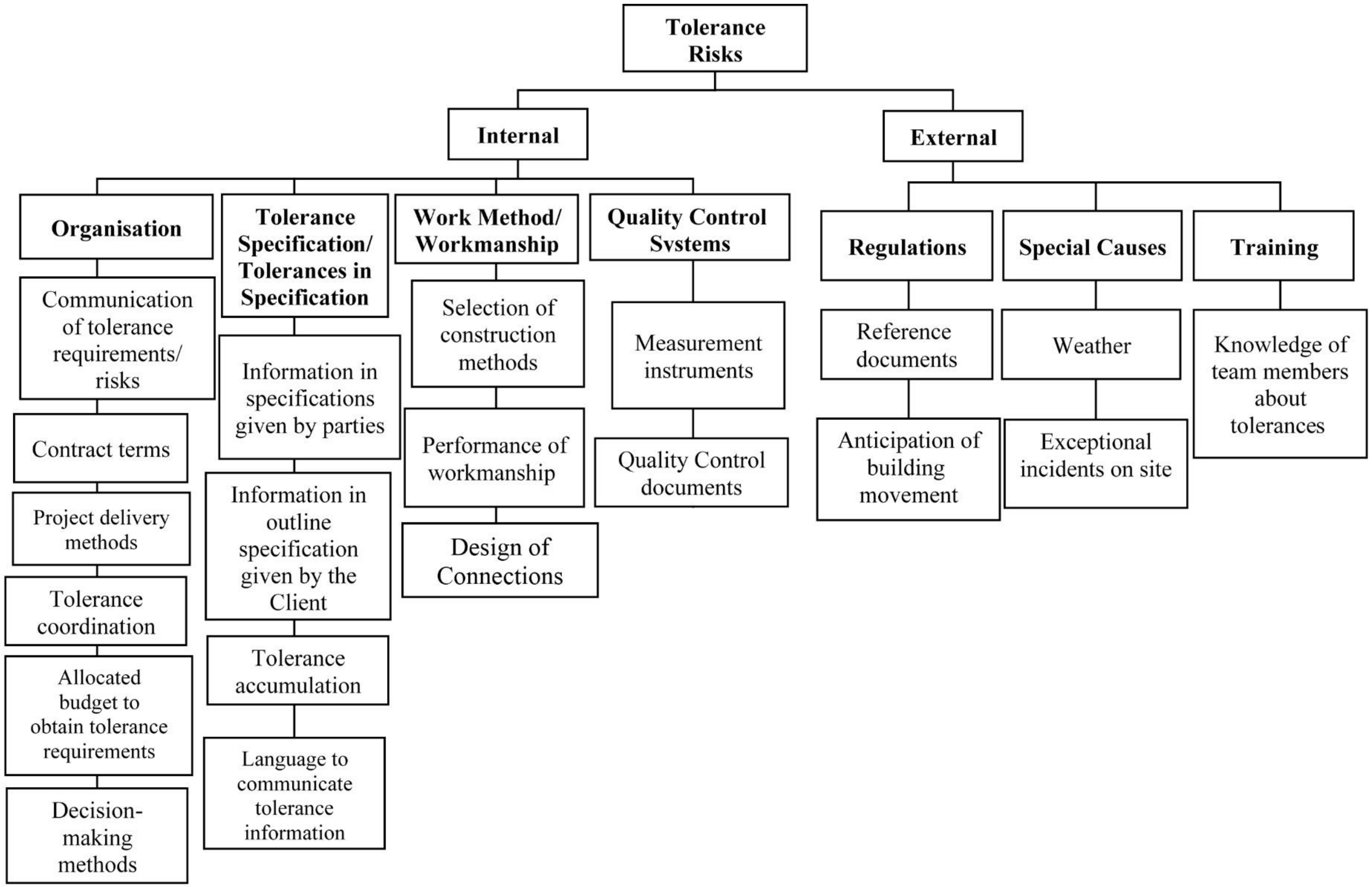



**Figure 6-73. Tolerance hierarchical risk break down structure**

It is shown in Figure 6-73 that Organisation, Tolerance Specification, Work Method, and Quality Control Systems are the risk factors under the 'Internal Risks' category, and Regulations, Special Causes and Training are the risk factors under the 'External Risks' category. The risk factors are broken down into various sub-risk factors. This is to further ascertain the origin of each risk. Once the risk factors are determined, the countermeasures to mitigate the risks can be easily decided upon as the risk factors provide a generic vision about the countermeasures needed to mitigate their associated risks.

The identified tolerance risks may depend on the existence of one or more risk factors. For instance, there may be a risk of excessive deviation of flatness of concrete slabs in composite floors. This risk can originate from poor workmanship and regulations (e.g. restrictive and non-achievable tolerances). The former risk factor is an internal risk and there is more control over it whereas the latter is an external risk.

Tolerance risks, like other typical risks in construction, are assumed to be a function of the interaction of probability and severity. Hence, the tolerance risk assessment process includes the assessment of the probability and the likelihood of tolerance risks. The impact of each risk is determined under the jurisdiction of the TMM Committee. This step makes the parties aware of the consequences of not addressing the tolerance risks.

To assess the probability of a tolerance risk, the likelihood of its corresponding risk factors and sub-factors should be investigated. The factors describe prevalent situations that can lead to tolerance problems; thus, it will be easier to decide the probability of tolerance risks based upon the individual influencing and known factors.

The terms for describing probability and severity of tolerance risks are shown in Table 6-39 and Table 6-40 respectively (explained in Section 2.7.3 and Appendix E). The impacts of tolerance risks should be considered based on the following performance measures: time needed for the modification process, cost of the modification process, cost of delay and waiting time, impact on the safety, and quality (serviceability)[21].

[21] These performance measures have been selected based on the most common consequences of tolerance problems identified in the literature (Explained in Section 2.1) and perceived during the empirical studies (summarised in Section 4.3).

**Table 6-39. Terms for ascribing probability of tolerance risks**

| PROBABILITY | DESCRIPTION |
|---|---|
| Very high | Expected to occur |
| High | Very likely to occur |
| Medium | Likely to occur |
| Low | Unlikely to occur |
| Very low | Very unlikely to occur |

**Table 6-40. Suggested terms for ascribing severity of tolerance risks**

| SEVERITY | TIME NEEDED FOR THE MODIFICATION PROCESS | COST OF THE MODIFICATION PROCESS | COST OF DELAY AND WAITING TIME | QUALITY (SERVICEABILITY) |
|---|---|---|---|---|
| Extreme | Extremely time consuming | Extremely costly | Extremely costly | Extremely Poor |
| High | Very time consuming | Very costly | Very costly | Poor |
| Medium | Time consuming | Costly | Costly | OK |
| Low | OK | OK | OK | Above average |

A checklist for the tolerance risk assessment is shown in Table 6-41. The headings in the checklist are explained as follows:

- **Foreseeable potential tolerance risks identified**: The identified tolerance risks are written in the second column. One way to help identify tolerance risks is to investigate whether the architectural and engineering designs, and the assembly process, are compatible with the specified tolerance requirements. The focus of the TTM Committee, when performing tolerance risks assessment, should be on the identified KCs in order to focus on the most important contributors to the risk. The following question should be addressed for every KC identified earlier: "what can go wrong if a KC has more variation than allowed, from the pre-construction stage to the construction stage?". Moreover, the classes of tolerances should be taken into account when identifying tolerance risks. It is assumed that the selection of particular and special classes of tolerances result in the risk of not achieving the required (i.e. more restrict) level of accuracy;
- **Risk ownership**: The third column indicates the party who has the most control over the source of the risk;
- **Affected parties**: The fourth column indicates the party or parties that are sensitive to the tolerance risk in a way that the accuracy and functionality of

their work can be adversely affected. Recognition of the affected parties is imperative in the tolerance risk assessment process as the affected parties should be primarily involved in the decision making process. In fact, because KCs have already been identified for the sub-assemblies, it is easy to recognise the affected parties;

- **Description**: The fifth column describes the tolerance risk, sources of the risk, impacts of the risk on the involved parties, and the associated consequences of the risk;
- **Risk factor/sub-risk factors**: The sixth column indicates the factors that trigger the tolerance risk;
- **Probability and severity**: The seventh and eighth columns are about the likelihood and impact of the risk. To find the probability and severity of tolerance risks, the following questions should be addressed for the identified tolerance risks:
    - What is the probability that the KC may not be addressed?
    - What are the impacts if a KC is not addressed on cost, time, safety and quality (serviceability)?

The Tolerance Risk Assessment step includes identification of tolerance risks, analysis of tolerance risks and mitigation of tolerance risks. The identification of tolerance risks and analysis of tolerance risks are relevant to part one of TMS, 'Identification of Tolerance Risks/ Requirements'. The mitigation of tolerance risks is relevant to the second part of TMS, 'Plan to Achieve Tolerance Requirements / Mitigate Tolerance Risks'. Hence, the Tolerance Risk Assessment step will be completed in Section 6.3.3.5.

**Table 6-41. Checklist for the tolerance risk assessment**

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | **TOLERANCE RISK ASSESSMENT** | | | | | | **JOB NO.** | |
| | | Activity | Tolerance Management | | | | | Date | |
| | | Project / Location | | | | | | Ref | |
| **NO.** | Foreseeable Potential Tolerance Risks Identified | Affected Parties | Description | Risk Factor / sub-risk factors | Probability | Severity | Risk Ownership | Strategy Options | |
| | | | | | | | | | |
| | | | | | | | | | |
| | | | | | | | | | |

### 6.3.3 *Part Two: Planning the Achievement of Tolerance Requirements/Mitigation of Tolerance Risks*

#### 6.3.3.1 Selection of Reference Documents to Adopt Tolerance Values for the Identified Key Characteristics

The TTM Committee must determine which reference documents the tolerance values for the identified KCs are adopted from. The main objective of this step is to ensure that tolerance values adopted for KCs are compatible with each other. This step is important mainly because specifications often contain a list of reference documents and many of them may not even apply to the project (explained in Section 2.8.1). This step is a starting point to ensure designers and construction trades involved in the TTM Committee are fully informed of the relevant reference documents from which they can adopt tolerance values for the KCs. Moreover, there may be instances where there are different reference documents containing inconsistent tolerance information for the same component. In particular, some of the reference documents written by the British Standard Institute (BSI) have been recently superseded by the European reference documents. However, the superseded reference documents may still be used in projects by mistake (explained in Section 4.1.2.1). As a general rule, if various tolerance values are found for a feature, the strictest tolerance value is adopted (i.e. the reference document which prescribes the strictest tolerance value is used) (British Standards Institution, 2009a).

#### 6.3.3.2 Assignment of Tolerance Values for the Identified Key Characteristics

In this step, the TTM Committee should assign tolerance values for the identified KCs. Tolerance values are adopted from either reference documents or are based on the experience of the members of the TTM Committee[22]. Under all circumstances, the TTM Committee must first refer to reference documents, as this is a common practice in the industry and is supported by regulatory frameworks. The findings from reference documents are the basis for any further decisions regarding the assignment of an optimal tolerance value.

[22] If Tolerance Manuals exist in an organisation, tolerance values can be adopted based on the previous experiences as well. Tolerance Manuals will be explained in Section 6.3.6.2.

The TTM Committee should list the identified KCs, recognise the sources of variation that may influence KCs, and find the limits for those variations. This step should be executed under the jurisdiction of the TMM Committee, specifically for each project. This is because each project has its own KCs (e.g. floor thickness, floor flatness, plumpness of columns).

After the identified KCs for each sub-assembly are listed, the TMM Committee should specify the lower and upper limits for the induced and inherent sources of variations that influence the KCs. The sources of variations are as follows (explained in Section 2.3.1) (the first three are induced sources of variations and the remaining are inherent sources of variations):

- Construction/manufacturing/fabrication deviations;
- Erection deviations;
- Setting-out deviations;
- Deflection due to: (a) self-weight of the building structure, (b) weight of the cladding system, and (c) imposed loads;
- Axial shortening of concrete columns and walls in tall buildings;
- Lateral movements;
- Drying shrinkage of concrete elements, including differential drying shrinkage;
- Moisture movement;
- Settlement in foundations, especially differential settlement;
- Changes in temperature.

For example, in a sub-assembly comprised of the edge concrete beam and cladding system, the straightness of edge concrete beam is a KC. Such KC may be affected by the deflection due to the self-weight of the building structure, the weight of cladding and imposed loads, drying shrinkage, moisture movement, settlement in foundations, and changes in temperature. Ideally, tolerance values should be assigned to each of these sources of variations. If this is not possible, according to (CONSTRUCT Concrete Structures Group, 2010), the total deflection post construction can be calculated through span/300, limited to 20 mm.

In three particular situations, the TTM Committee should collectively find tolerance values for sources of variations affecting KCs rather than referring to the reference documents. These three situations are as follows:

- When there is no recorded tolerance information for a KC. If this is the case, the tolerance information should be obtained directly from the TTM Committee, in particular the manufacturers and contractors (explained in Section 2.4);
- When the TTM Committee decides to apply a particular class of tolerances to a KC. In this case, reference documents are used as a basis but the committee should choose more restrictive tolerances to ensure the design intent is satisfied (explained in Section 2.3.3);
- When the TTM Committee reaches a conclusion that the tolerance information found in the reference documents is not constructible or does not guarantee that the design intent for a KC is satisfied (explained in Section 2.4).

It is important that the TTM Committee holds a trade-off between the cost of a higher accuracy and then accordingly the cost of construction. The design intent should yield to the realities of constructability and economics. Tolerance values and work methods needed to achieve tolerance requirements should be decided by negotiation and compromise between what designers, especially architects, intend to achieve and what construction trades and the manufacturing supply chain can economically deliver (explained in Section 2.4). The negotiation must evolve around KCs and not the numerous connections and dimensions that do not impact upon the function of the building, as this would not be beneficial from an economic and time management point of view. The TTM Committee should avoid assigning restrictive tolerances for all KCs if there is a tolerance risk, as this approach often increases the construction cost but does not necessarily prevent tolerance problems.

#### 6.3.3.3 Determination of Characteristic Accuracy

In essence, even if the normal class of tolerances are assigned to a KC, there will be variations that exceed the specified limit (explained in Section 2.3.2). Hence, it is important that the TTM Committee determines the Characteristic Accuracy for each of the identified KCs. More specifically, the committee should decide on: (a) the Systematic Deviation, and (b) multipliers before the Standard Deviation (SD) for each KC. The basis of selecting the Systematic Deviation information is provided in (British Standards Institution, 1990). However, the information in this reference document is outdated (explained in Section 2.3.2) and, therefore, the values should be selected under the jurisdiction of the TMM Committee[23]. In particular, contractors who are expected to have a better understanding of the achievable Systematic Deviation should first review the values stated in (British Standards Institution, 1990), critically evaluate their appropriateness, and then propose optimal values if needed.

For example, the distance between the steel columns can be a KC because the cladding panels should be fitted between them. In the design, the distance between the columns in the envelope of the building is 2000 mm. According to (British Standards Institution, 1990), the Systematic Deviation is -1.3 mm, that is the average distance between the columns will be 1998.7 mm (rather than 2000 mm). First, it should be discussed within the committee whether this value is the optimal. Assume that the committee decide to proceed with the value stated in (British Standards Institution, 1990). From the previous steps, the committee already knows which reference document is to be used to adopt tolerance values for the selected KC (i.e., the distance between the steel columns). If the committee is using the British Constructional Steelwork Association (2010) guidance, then the deviation in distance between columns can be 10 mm (i.e. 2SD = 10 mm)[24]. Hence, 1SD in this case is 5 mm[25]. The committee now can proceed as follows:

- If 1SD (i.e. 5 mm) is selected, 68.27% of distances between columns will be between 1993.7 mm and 2003.7 mm (i.e. 1998.7 ± 5mm);
- If 2SD (i.e. 2 * 5 mm) is selected, 95.45 % of the distances between the columns will be between 1988.7 mm and 2008.7 mm (i.e. 1998.7 ± 11 mm);
- If 3SD (i.e. 3 * 5 mm) is selected, 99.73% of the distances between the columns will be between 1983.7 mm and 2013.7 mm (i.e. 1998.7 ± 16.5 mm).

The committee should take into account if: (a) 1SD is chosen, then 1 in 3 is out of tolerance, (b) if 2SD is chosen, then 1 in 22 is out of tolerance, and (c) if 3SD is chosen, then 1 in 370 is out of tolerance. In other words, more risks are now identified and they should be added to the already identified risks. Moreover, it should

[23] And by using other sources of information such as Tolerance Manuals, which will be explained in Section 6.3.6.2.

[24] The reference documents do not clearly state that to what Characteristic Accuracy they are working. However, as far as it is know, 2SD is used (explained in Section 2.3.2).

[25] According to British Standards Institution (1990), 1SD is 5.5 mm. If there is any inconsistency between the reference documents, always the most restrictive value is chosen. Hence, British Constructional Steelwork Association (2010) should be used.

be noted that if 2SD is chosen, then the normal class of tolerance is applied, but if 1D, 1.5D or other smaller multipliers than 2 is chosen, the special class of tolerance is applied.

#### 6.3.3.4 Evaluation of Combined Deviations (Tolerance Analysis)

When components are put next to each other, dimensional and geometric variations accumulate. The accumulation of deviations must be evaluated, especially by the tolerance coordinator, to ensure that deviations of the identified KCs in sub-assemblies will be within the specified limits and will not be adversely influenced by the accumulation of deviations. For example, when trying to fit a slider door in a frame opening, the distance between the top of the surface of the bottom concrete slabs, and the lower surface of the above concrete slabs in a floor, is a KC. This KC is highlighted in Figure 6-74 using a red line. A set of various variations affect this KC and should be taken into account. Such deviations are: flatness of concrete slabs, thickness of concrete slabs, level of concrete slabs, setting out of the slider door, and straightness (deflections) of concrete slabs. If the combined deviations exceed the specified tolerances for this KC, the slider door will not fit or there would be gaps in the interface between the door and slabs. Generally, despite of the fact that all the components in a sub-assembly may be within the specified tolerances, the cumulative effect of deviations may result in a KC being out of tolerance.

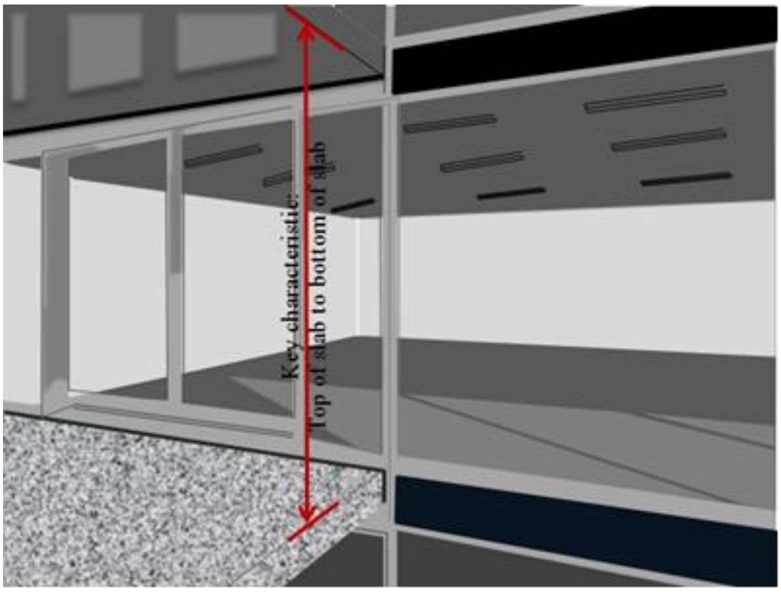



**Figure 6-74. Illustration of a KC when trying to fit a sliding door**

The TTM Committee, in particular the tolerance coordinator, should perform the tolerance analysis consistently throughout the design process. This is to reliably ensure adjacent components fit, function as intended and are aesthetically pleasant. The accumulated deviations in sub-assemblies must be less than or equal to the tolerance initially specified by the TTM Committee. If after performing the tolerance analysis, it transpires that components clash, there is an unacceptable gap, or generally KCs are not satisfied, designs should be changed.

The corresponding combined deviation due to manufacturing/construction/fabrication tolerances, erection tolerances and setting-out tolerances, called $D_1$, can be calculated using the root sum square (RSS) method (Equation 2). In Equation 2, $X_1$ represents manufacturing / construction / fabrication tolerance, $X_2$ represents erection tolerance and $X_3$ represents setting-out tolerance:

Equation 2. $$D_1 = \sqrt{(X_1)^2 + (X_2)^2 + (X_3)^2}$$

Deviations due to inherent deviations ($D_2$) (e.g. deflection, temperature change, moisture content, etc.) are added arithmetically to D1 using the worst-case method. Hence, the Total Deviation (TD) can be calculated using Equation 3:

Equation 3. $$\text{Total Deviation (TD)} = D_1 + D_2$$

For instance, in the example set out above for the sliding door, the distance between the top of slab to the bottom of slab in a floor is 3 m. Assume that the tolerance for flatness of concrete slabs is ±5 mm, the tolerance for thickness of concrete slabs is ±8 mm, the tolerance for level of concrete slabs is ±6 mm, the tolerance for setting out of the slider door is ±4 mm, and the tolerance for the straightness (deflections) of concrete slabs is between 0 and -10 mm. Hence, the combined induced deviations are calculated using Equation 4:

Equation 4. $$D_1 = \sqrt{(\pm 5)^2 + (\pm 8)^2 + (\pm 6)^2 + (\pm 4)^2} = 11.87 \text{ mm}$$

According to Equation 4, the combined induced deviation in the selected KC is ±11.87 mm. This deviation should be arithmetically added to the tolerance value for the inherent deviation, that is -10 mm. As a result, TD will be either +11.87 mm – 10 mm or -11.87 mm – 10 mm. That is, the distance between the top of the slab to the bottom of the slab in a floor can be either 3000 mm + 1.87 mm = 3001.87 mm or 3000 mm – 21.87 mm = 2978.13 mm.

When the RSS method is used there is a probability that tolerance problems occur, while the worst-case method should be used when there is no room for a defect and a 100 per cent conformance to requirements is intended. Hence, it should be argued that if a particular class of tolerance is applied to a KC or, generally a 100 percent acceptance is needed for a KC, then it is suggested that the Tolerance Coordinator only use the worst-case method for all variations affecting that KC. For instance, in the example above, if the particular class of tolerances is applied to the selected KC, Equation 4 should be replaced with Equation 5, thus applying the worst-case method:

$$\text{Equation 5. } D_1 = 5\text{ mm} + 8\text{ mm} + 6\text{ mm} + 4\text{ mm} = 23\text{ mm}$$
$$\text{or } D_1 = -5\text{ mm} - 8\text{ mm} - 6\text{ mm} - 4\text{ mm} = -23\text{ mm}$$

According to Equation 5, the combined induced deviation in the selected KC is ±23 mm. This deviation should be added to the tolerance value for the inherent deviation, which is -10 mm. As a result, the total deviation will be either +23 mm – 10 mm or -23 mm – 10 mm. That is, the distance between the top of the slab to the bottom of the slab in a floor can be either 3000 mm + 13 mm = 3013 mm or 3000 mm – 33 mm = 2967 mm.

### 6.3.3.5 Tolerance Risk Assessment (Part Two)

Up to this stage, tolerance risks have been identified and analysed. The TMM Committee should now collectively find appropriate strategies to mitigate those risks while holding a trade-off between the satisfied KCs, the incurred costs and needed time. Addressing the following two questions is necessary to fulfil this step:

- What should be done and what options are available to mitigate tolerance risks?
- Which actions optimise the trade-off between the mitigation options and time/cost needed for them?

The countermeasures that need to be taken by the risk owner or other parties should be visibly described in this step. As such, ambiguous descriptions like what is conventionally established in contracts to transfer tolerance risks to other parties must be strictly avoided.

To find an optimal countermeasure to mitigate tolerance risks, the TTM Committee should account for the following alternatives (explained in Appendix E): risk avoidance/mitigation, risk insurance, and risk acceptance. These alternatives are explained below:

- **Risk avoidance/mitigation**: The TTM Committee attempts to eliminate the identified tolerance risks or mitigate their adversarial impacts;

- **Risk insurance**: If the financial loss due to a tolerance risk is expected to be high, the TMM Committee should shift the risk of financial loss to a third party (insurance for construction defects);
- **Acceptance**: If the probability of a tolerance risk is high, the TMM Committee should recommend the general contractor establishing the contingency money. This is to cover the amount of time and money needed to modify defects associated with tolerances;

The second and third strategies are clear but the first strategy needs further explanation. An approach (perhaps among many) is envisioned to avoid/mitigate tolerance risks, namely minimising adversarial impacts of variations. This approach will be explained further in the next section.

### *6.3.3.5.1Reducing impacts of variations influencing KCs*

Two methods to reduce the impact of variations influencing KCs are: the selection of appropriate connections, and the selection of an appropriate load sequence. It should be noted that there might be more methods but two of them are given in this version of TMS.

#### 6.3.3.5.1.1Selection of appropriate connections

Assume that the space between two components is a critical dimension (i.e. KC), and there is a risk that either there would be a space exceeding than what has been specified between the components or the components would clash together. The committee may choose an appropriate type of connection to mitigate the risk. For example, the covered connection can be used if the tolerance analysis particularly shows there is a risk of an exceeding space, or a sliding connection should be used if there is a risk that the components will clash together. A more tangible example would be when the height of floor to floor is critical to fit curtain walls. The height can be affected by a deflection of the floors. An adjustable connection embedded in the curtain walls can accommodate (i.e. absorb) the resultant variations. Note that the selection of appropriate connections highly depends on the type of components and variations. Table 6-42 provides a list of connections predominately utilised in construction along with a description of the type of variations that can be accommodated by each connection (explained in Section 2.11).

**Table 6-42. Types of connections and types of variations that can be accommodated by each connection**

| CONNECTIONS | DESCRIPTION |
|---|---|
| Butt connection | It cannot accommodate any variations unless the jointing components are slightly separated. In this case: (a) minor variations in size and position of components, and (b) minor variations due to building movement, can be accommodated. The space between the components in this type of joint should be filled with sealant. |
| Concealing connection | It can accommodate minor variations: (a) in size and position of components, and (b) due to building movement. Unlike a butt joint, it does not require sealant. |
| Covered connection | It can accommodate both small and large variations and is used when there must be a clearance between two components. Its drawback is that it imposes a particular appearance to the joint. |
| Sliding connection | It can accommodate large variations. Unlike covered and concealing joints, it does not require a third component to cover the joint. Hence, it does not impose a particular appearance to the joint. |
| Offset connection | It can accommodate only minor variations due to building movement. If a space between components is created in this joint, it can also accommodate minor variations in size and position of components. |
| Adjustable connection | It can accommodate both minor and large variations: (a) in size and position of components, and (b) due to building movement. It is mainly used when factory-made components are put next to in-situ components. |
| Expansion connection | It can accommodate variations due to building movement caused by expansion of components. |

### 6.3.3.5.1.2Selection of an appropriate load sequence

The load sequence is determined by: (a) the assembly process, (b) the occupancy of the building, and (c) the maintenance of the building. Loads applied to the building after the building is operated depend on the purpose of the building and how it is maintained, therefore the loads should be accurately anticipated as there is not much control over them. However, the committee can make decisions about the assembly process where the identified KCs would be less subject to variations. To address the load sequence, ideally, the construction planner of the project and structural engineer should be invited to the committee at this stage.

There are five milestones when considering the load sequence (Table 6-43) (according to the empirical study three, summarised in 4.4.1.5). The first three are related to the assembly process and the last two are related to the operation of the building. The structural engineer should calculate the resultant deflection of floor slabs and beams after each milestone. The committee should then investigate the impact of the deflection on KCs. The most tangible impact is on the floor to floor height that is often a KC.

The time point at which the cladding is installed in the construction programme is very important. This is because the cladding system should be capable of absorbing deviations due to its self-weight, the weight of finishes, and any other loads applied afterwards, otherwise one of the KCs (i.e. the floor to floor height) will not be satisfied. Hence, the committee should determine whether the cladding should be installed first or along with the finishes. The location of the stock of heavy inventories on floors should be planned. This is because there may be unplanned deflections due to the weight of those inventories. Also, it is important to investigate whether introducing any heavy machinery/equipment into the building when it is in operation will negatively impact a KC.

**Table 6-43. List of milestones when considering the load sequence and the corresponding loads being applied to the building**

| NO. | MILESTONES | CORRESPONDING LOADS |
|---|---|---|
| 1 | When the structure is erected | The dead load derived from the self-weight of the structure |
| 2 | When the cladding is fixed to the structure | The superimposed dead load derived from the weight of cladding |
| 3 | When finishes on floors and ceilings (e.g. services, suspended ceilings and raised floors, mechanical pipes) are installed. | The superimposed dead load derived from the weight of the finishes |
| 4 | When heavy inventories are stocked on floors | The imposed load derived from the weight of heavy inventories |
| 5 | When the building is occupied | The imposed load derived from the occupancy of the building |
| 6 | When heavy machineries/equipment are brought to the building for maintenance purposes | The imposed load derived from the weight of machineries/equipment (e.g. a cherry picker) brought to the building for cleaning, etc. |

Eventually, the committee should provide the following information:

- Deflection of slabs and beams due to the self-weight;
- Deflection of slabs and beam due to the superimposed dead load (i.e. weight of the cladding and finishes);
- Deflection of slabs and beams due to the imposed load (i.e. occupancy of the building, temporary machineries/equipment);
- Total deflection of slabs and beams.

The importance and the impact of load sequence is demonstrated through the following example. It is assumed that the dead load deflection of an edge beam is 10 mm, the deflection due to the installation of a lightweight cladding is 5 mm, the deflection due to the weight of the finishes is 15 mm, and the Imposed Load (i.e. live load, due to the occupancy) deflection is 5 mm. Given that deflections are cumulative and should be arithmetically added together, the total deflection of this edge beam will be 35 mm. In this example, the cladding system is fixed first and then the finishes are installed. Hence, the cladding will not experience the 10 mm dead load deflection because that has already occurred before the installation of the cladding. In fact, the cladding will experience the deflection due to its self-weight (i.e. 5 mm), the weight of finishes (i.e. 15 mm) and imposed loads (i.e. 5 mm), which is 25 mm in total. If the assembly process were different in such a way that the finishes were installed first and then the cladding, the deflections due to the cladding self-weight and the imposed loads would need to be incorporated in the fixings of the cladding only. This means that the cladding has to be capable of absorbing a deflection of 10 mm.

To illustrate the tolerance risk assessment further, tolerance risks of case two are analysed. The tolerance risk assessment for case two is given in Table 6-44.

**Table 6-44. Tolerance risk assessment for case two**

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | TOLERANCE RISK ASSESSMENT | | | | | JOB NO. | |
| | | Activity | Tolerance Management | | | | Date | |
| | | Project / Location | | | | | Ref | |
| **NO.** | Foreseeable Potential Tolerance Risks Identified | Affected Parties | Description | Risk Factor / sub-risk factors | Probability | Severity | Risk Ownership | Strategy Options |
| **1** | Misalignment of Doorways | Cladding and steel subcontractors | The columns, parallel flange channels (PFCs), and cladding rails at both sides of a doorway may not be parallel and aligned. This is because the cladding rails and PFCs in the current design are free-standing and flexible. Making one doorway aligned can make the PFCs and claddings rails misaligned in the adjacent doorway, because those components are involved in two doorways. This misalignment makes it difficult to fit the doorframe. | **Work method/Workmanship**- selection of construction method<br>Tolerance specification/ Tolerances in specifications- Design of connection<br>**Organisation** / Tolerance coordination<br>**Organisation** / contract terms | | | Steel subcontractor | 1. The design should change in a way that PFCs and cladding rails are fixed to the ground (i.e. Reducing sources of variations influencing KCs).<br>2. The design should be changed to have the cladding rails all the way through between doorways.<br>3. If the actions above are not possible (e.g. costly to change the design), the site engineer must be available on site when erecting the columns and other components involved in the doorways to ensure that they are aligned and parallel. |

**Table 6-44 Continued**

| NO. | TOLERANCE RISK ASSESSMENT | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 2 | Wavy Purlins | Cladding and steel subcontractors | Purlins can be misaligned due to the selection of wrong sections for them, careless installation (deviations during the construction process), rotation under self-weight or loading out, and deviation of primary steelwork erection. When the purlins are not in their nominal positions, envelope fasteners cannot reach the purlin and the cladder subcontractor has to stretch the roof cladding system. The attachment failure and end laps can interrupt the installation of roof sheeting, and can adversely affect the performance of the building envelope which means that there can be both air and water leaks on the roof. | **Work method** / **workmanship –** performance of workmanship<br>**Organisation** / Tolerance coordination and contract terms<br>**Quality control systems** / measurement instruments and quality control documents | | | Steel subcontractor | 1. Control the purlins on the roof regularly (to be done by the steel erectors).<br>2. Ensure the selection of purlins has the appropriate sections which satisfy the project requirements. |

**Table 6-44 Continued**

| NO. | TOLERANCE RISK ASSESSMENT | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 3 | | Lack of fit in the steelwork if erected in two pieces | If for any reason, the steelwork cannot be erected consistently and the steel subcontractor has to connect the two erected sides together, there is a risk of lack of fit between these two sides, because:<br>1. The orientation of the two sides are opposite to each other and there is an overlap between the two sides so one or more structural member(s) cannot be fitted; or,<br>2. The deviations of the two sides are towards the same direction but the fasteners cannot reach each other and there is a gap between two pieces. | **Work method** / **Workmanship** - selection of construction method<br>**Organisation** / communication and tolerance coordination<br>**Quality control systems**/ quality control process | | | Steel subcontractor | 1. The first line of the columns should be as plumb as possible by having the surveyor on site when erecting them or by using a laser plumb. This is because the deviation of the first line of the steelwork to a great extent affects the deviation of the whole steelwork.<br>2. The starting point and direction of erection should be established at the design stage. If the decision was made to erect the steelwork in two pieces:<br>The deviation of the first erected side should be carefully monitored to avoid excessive accumulation of deviations in the last gridlines;<br>The deviation of the second erected side should be compatible with the deviation of the first erected side.<br>The surveyor should be available on site when erecting the second side. |
| 4 | Lack of Fit for Personnel Doors | | If the doorframes of personnel doors are not plumb and square, the personnel doors cannot be fitted in square as well. This is because the joint between the door and the galvanised plate of flashing does not allow any deviations of the columns. | **Organisation** / tolerance coordination and communication<br>**Tolerance specification** / tolerance accumulation<br>**Work method** / performance of workmanship | | | Steel subcontractor and cladding subcontractor | 1. The simplest technique to avoid this problem is to design the doors around 40 mm smaller so there will be 20 mm gap.<br>2. The posts should be controlled regularly.<br>3. The squareness of doorframes should be controlled properly. |

#### 6.3.3.6 Completion of the Tolerance Agreement and Design Form

Table 6-45 shows a Tolerance Agreement and Design Form. In this step, a document called the Tolerance Agreement and Design Form, is prepared. In this document, all the identified KCs are listed. The main purpose of completing the Tolerance Agreement and Design Form is threefold:

- **To specify** the permitted variations of the identified KCs. A KC can be on a component or in a sub-assembly. In the latter case, tolerances should be specified for every component in a sub-assembly;
- **To define** the contractual relationships of the parties involved in the design of components where their variations affect KCs;
- **To establish** a shared understanding among members of the TTM Committee about the identified KCs, the permitted variations of each KC, and who will design the components, influencing the variations of the KCs.

The completion of the Tolerance Agreement and Design Form by the TMM Committee should start right at the beginning of the process. The form should be developed as the information in prior steps are being collected and crystallised. The information that should be listed in this form and actions that should be taken are explained next.

***Key Characteristics (KCs)*:** KCs identified in prior steps are listed.

***Component/Critical Sub-assembly***: The components or critical sub-assemblies (comprising two or more components), which contribute to the achievement of a KC, are listed.

***Permitted variations for KCs according to the reference documents / associated reference documents***: Permitted induced and inherent variations adopted from the existing reference documents are listed. The reason for having this column is that the TTM Committee will be able to compare the permitted deviation stated in the reference documents against the final agreed deviation by the TTM Committee; thus, any difference between the standard tolerances and the final agreed tolerances by the TTM Committee will be transparent. Moreover, the reference documents, from which permitted variations are adopted, are listed in this column.

***Agreed Variation***: The committee should decide whether the stated variations in reference documents satisfy the achievement of the identified KCs. If not, permitted variations for KCs should be determined and agreed. To judge whether standard tolerances are optimal and, if not, what tolerance should be allowed, the TTM Committee needs two pieces of information as follows:

- **Tolerance risks**: The information comes from the 'Tolerance Risk Assessment' step. One of the countermeasures for risk avoidance/mitigation can be the assignment of more stringent tolerances. If that approach is followed, the committee may decide to assign more restrictive tolerances;
- **Tolerance analysis**: In fact, the occurrence of exceeding variations other than originally specified on a KC, due to accumulation of variations, is a risk and should have been found earlier in the project. The reason for considering information stemming from the tolerance analysis as a separate piece of information is to highlight its importance. If it turned out that the accumulation of deviations may impact on a KC, the committee may decide to assign more restrictive tolerances (i.e. variation reduction).

The committee should always bear in mind: (a) the trade-off between the cost and time needed for specifying a tighter tolerance versus cost of rework, and (b) the constructability of tighter tolerances before assigning them. In this context, constructability means how easily tighter variations for a KC can be obtained on site without any rework.

***Characteristic Accuracy / Systematic Deviation***: When a more stringent or even a lenient tolerance is selected, there are two approaches to determine the Characteristic Accuracy:

- The TTM Committee may confirm that the Characteristic Accuracy of a tolerance value stated in a reference document meets 2SD, and the multiplier for the SD of the agreed tolerance should be determined accordingly. For example, if the normal tolerance of ±20 mm for flatness of in situ concrete slabs is stated in (CONSTRUCT Concrete Structures Group, 2010) but the committee decides to assign a tighter tolerance of ±15 mm, then the multiplier for SD of the agreed deviation will be 1.5. Therefore, 86.64% of the measurement results are expected to be within the limits;
- The TTM Committee may decide that the Characteristic Accuracy of the agreed tolerance (not the tolerance value stated in reference documents) is 2SD. Therefore, by assigning the agreed deviation, 95.45% of measurement results are expected to be within the limits.

The second approach is arguably more logical compared to the first approach. This is because it does not seem practical to choose a more stringent tolerance while allowing more measurement results to be out of tolerance (i.e. increasing the risk of tolerance problems).

Moreover, in this section, the Systematic Deviation that has been selected in prior steps should be listed for each and every component.

***Design Responsibilities***: The contractual relationship between parties involved in the design of components, where their variations affect KCs, is described in this section. The task of delivering design in a way that KCs are satisfied is clearly allocated to designers and they will be contractually obliged to account for tolerances in their designs. Four parties are conceivable to take the responsibility of design, namely principal designers, specialist subcontractors, structural engineers and other specialists. Their roles can be Lead Designer, Designer, Assistant and advisor, and Informed. The terms Lead Designer and Designer are commonly used in construction documents, including the reviewed documents in case one and their definitions are clear. The last two roles have been devised specifically for this document and their descriptions are as follows:

- **Assistant and Advisor**: The parties who should be consulted with due to their knowledge and expertise, such as construction manager, quality assurance, Tolerance Coordinator, structural designer, design manager, site engineer, etc.;
- **Informed**: The parties who need to know the status of the design progress, quality of the work, and any concerns raised/decisions made before, during, or after the construction of important components for the achievement of KCs.

To illustrate this point further, a completed Tolerance Agreement and Design Matrix for case two is given in Table 6-46.

**Table 6-45. Tolerance Agreement and Design Form**

<table>
<tr><td colspan="2"></td><td colspan="8">**TOLERANCE AGREEMENT AND DESIGN FORM**</td><td>**JOB NO**</td><td>**XX**</td></tr>
<tr><td colspan="2"></td><td colspan="2">Activity</td><td colspan="6">Tolerance Management</td><td>Date</td><td>xx</td></tr>
<tr><td colspan="2"></td><td colspan="2">Project / Location</td><td colspan="6">xxx</td><td>Ref</td><td>xx</td></tr>
<tr><td rowspan="5">**NO.**</td><td rowspan="5">Key Characteristic</td><td rowspan="5">Component / Sub-assembly</td><td rowspan="5">Permitted Deviations according to the Reference Documents/ Associated Reference Documents</td><td rowspan="5">Agreed Deviation</td><td rowspan="5">Characteristic Accuracy</td><td colspan="4">Design Responsible</td><td colspan="2">**L**= Lead Designer</td></tr>
<tr><td rowspan="4">Principal Designer</td><td rowspan="4">Specialist Subcontractor</td><td rowspan="4">Structural Engineer</td><td rowspan="4">Other Specialists</td><td colspan="2">**D**= Design</td></tr>
<tr><td colspan="2">**AA**= Assistant and advisor</td></tr>
<tr><td colspan="2">**I**= Informed</td></tr>
<tr><td colspan="2">Remarks</td></tr>
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</table>

**Table 6-46. Completed Tolerance Agreement and Design Matrix for case one**

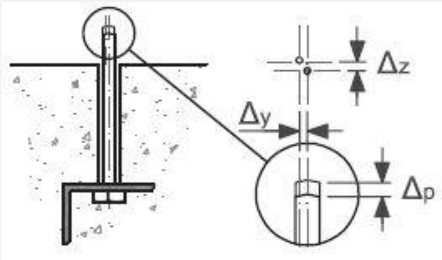
| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | **TOLERANCE AGREEMENT AND DESIGN MATRIX** | | | | | | | **JOB NO** | **XX** |
| | | Activity | Tolerance Management | | | | | | Date | xx |
| | | Project / Location | xxx | | | | | | Ref | xx |
| **NO.** | Key Characteristic | Component / Sub-assembly | Permitted Deviations according to the Reference Documents/ Associated Reference Documents | Agreed Deviation | Characteristic Accuracy | Design Responsible | | | | **L**= Lead Designer; **D**= Design; **AA**= Assistant and advisor; **I**= Informed |
| | | | | | | Principal Designer | Specialist Subcontractor | Structural Engineer | Other Specialists | Remarks |
| 1 | **Clearance** around the bolt  | Bolt | Δp = – 5mm (low) / + 25mm (high)<br>NSSS | Δp = – 5mm (low) / + 25mm (high) | 2SD | D | | L | | |

**Table 6-46 Continued**

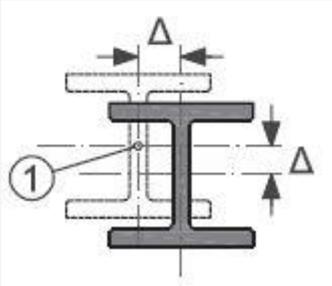
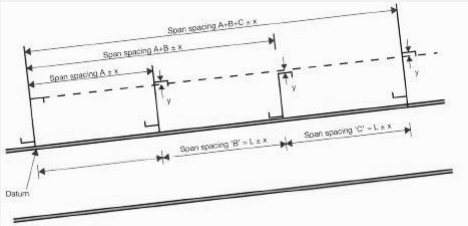
| NO. | TOLERANCE AGREEMENT AND DESIGN MATRIX | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| 2 | **Position of columns at base** – Deviations (Δ) of section centre lines from the specified position.   | Columns and base plates | Δ= 10 mm<br>NSSS | Δ= 10 mm | 2SD | D | | L | | |
| 3 | **Position of purlins –** Deviation of the intended position downslope (x)   | Purlins and steelwork | X = 10 mm (based on a 60 mm purlin flange)<br>Best Practice for the Specification and Installation of Metal Cladding and Secondary Steelwork | X = 10 mm | 2SD | L | D | AA | | |

**Table 6-46 Continued**

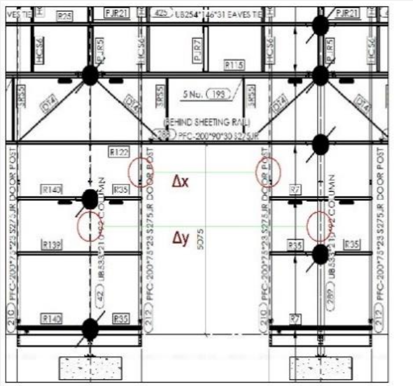
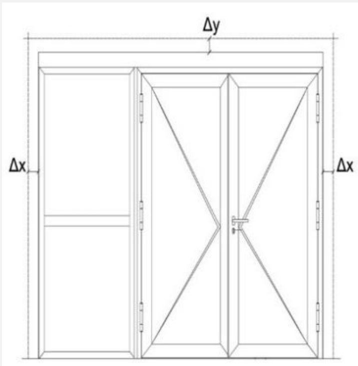
| NO. | TOLERANCE AGREEMENT AND DESIGN MATRIX | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| 4 | **Position of the primary and secondary steelwork in the doorways –** Deviation in the parallelism of the columns ($\Delta_x$) and deviation in the parallelism of the stanchions ($\Delta_y$) at both sides of the doorways.<br> | Steelwork | No information could be found | $\Delta_x$ = 8 mm<br>$\Delta_y$ = 10 mm | 1.5SD | L | D | I | | |
| 5 | **Clearance around the personnel door –** The minimum horizontal clearance ($\Delta_x$) and vertical clearance ($\Delta_y$) between the door and steelwork**.**<br> | Steelwork and doors | No information could be found | Minimum $\Delta_x$ = 10 mm<br>Maximum $\Delta_x$ = 15 mm<br>Minimum $\Delta_y$ = 8 mm<br>Maximum $\Delta_y$ = 12 mm | 2SD | L | D | | | |

**Table 6-46 Continued**

| NO. | TOLERANCE AGREEMENT AND DESIGN MATRIX | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| 6 | Clearance between flashing and cladding rail – The minimum clearance ($\Delta_y$).   | Flashing and cladding rail | No information could be found | Minimum clearance $\Delta_y$ =10 mm | 2SD | L | D | I | | |

### 6.3.3.7 Completion of the Tolerance Compliance Measurement Protocol

Thus far, KCs and permitted variations for them have been identified. However, three questions are yet to be answered: when, how, and by whom can the compliance of KC variations with specified limits be verified. The process of such verification is called Tolerance Compliance Measurement (TCM) and the document used at this stage to plan TCM is called the Tolerance Compliance Measurement Protocol (developed based on the existing inspection protocols, explained in Section 2.7.5). Table 6-47 shows a TCM protocol. The information needed by the TTM Committee to complete this protocol is explained below.

***Key Characteristics (KCs)***: KCs identified in prior steps.

Programmed Works Activity/Operation: A programmed activity in the project for which TCM is performed (e.g. structural steelwork, cladding and door installation).

***TCM Activity***: The exact activity in the process of TCM to measure variations of a KC (e.g. setting out, base survey, making columns plumb).

***Type of TCM***: There are two types of TCM, namely real-time control and inspection. Real-time control in TCM means measuring variations of a KC at the same time as the corresponding activity/operation progresses. Inspection concerns the measurement of variations after the corresponding activity/operation, or part of it, is completed. When a project does not have an internal surveyor, TCM is likely in the form of inspection because external surveyors normally visit the site after the completion of a certain apportionment of the programmed works.

***Method for TCM***: The method to measure variations of a specific KC is described here. The description of the method includes what measurement instrument is used, where the instrument should be located, where the datum is, etc.

***Controlling reference documents***: The reference document(s) describes the permitted variation, acceptance criteria, and the way TCM should be performed. The Tolerance Agreement and Design Form should be considered as a controlling reference document for this step. If a piece of information is missing, other documents, such as specifications, standards, design notes, drawings etc., are considered as the controlling reference document.

***Responsible for TCM***: The person or party who has the knowledge and instruments required to perform the TCM should be determined. Mainly, this is to specify whether an internal or external surveyor is responsible for measuring the variations of a KC.

***Intervention points: There are two intervention points in TCM***: the Hold Point and the Witness Point. The Hold Point is a verification point that does not allow the corresponding subcontractor to proceed without the approval of whether a variation of a KC is within the limits. The Witness Point is a recognised point where the subcontractor continues activities at hand while the verification of a compliance is carried out simultaneously. The Hold Point used when addressing a KC in a sub-assembly highly depends on the variations of individual components. For example, if the position and plumbness of cladding are KCs, the straightness of beams or the plumbness of columns should be verified before the cladding is installed. Hence, the Hold Point should be selected for these KCs to ensure the variations in the straightness of beams or the plumbness of columns is within the limits before the cladding subcontractor can begin to install the cladding panels.

***Frequency timing***: The timescale to carry out the TCM for every KC should be determined. Such timescale can be daily, weekly, at the end of every phase (e.g. completion of every phase of the steelwork), and at the start of every shift.

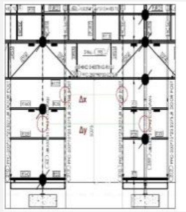
Table 6-48 presents an example of a completed TCM Protocol based on case two.

**Table 6-47. Tolerance Compliance Measurement Protocol**

<table>
<tr><td></td><td colspan="8">TOLERANCE COMPLIANCE MEASUREMENT PROTOCOL</td><td>JOB NO</td><td colspan="3"></td></tr>
<tr><td></td><td>Activity</td><td colspan="7">Tolerance Management</td><td>Date</td><td colspan="3"></td></tr>
<tr><td></td><td>Project / Location</td><td colspan="7"></td><td>Ref</td><td colspan="3"></td></tr>
<tr><td rowspan="5">NO.</td><td rowspan="5">Key Characteristic</td><td rowspan="5">Programmed Works Activity/ Operation</td><td rowspan="5">TCM Activity</td><td rowspan="5">Controlling Reference Document</td><td colspan="2" rowspan="3">Type of TCM</td><td rowspan="5">Methods to be Used for TCM</td><td rowspan="5">Responsible for TCM</td><td rowspan="5">Frequency/ Timing of TCM</td><td colspan="2" rowspan="3">Intervention Points</td><td>R= Real-time Control</td></tr>
<tr><td>I= Inspection</td></tr>
<tr><td>H= Hold Point</td></tr>
<tr><td rowspan="2">R</td><td rowspan="2">I</td><td rowspan="2">H</td><td rowspan="2">W</td><td>W= Witness Point</td></tr>
<tr><td>Remarks</td></tr>
<tr><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
</table>

**Table 6-48. Partially completed Tolerance Compliance Measurement Protocol for case two**

| TOLERANCE COMPLIANCE MEASUREMENT PROTOCOL | | JOB NO. | XX |
|---|---|---|---|
| Activity | Tolerance Management | Date | xx |
| Project / Location | xx | Ref | xx |

| NO. | Key Characteristic | Programmed Works Activity / Operation | TCM Activity | Controlling Reference Document | Type of TCM | | Methods to be Used for TCM | Responsible for TCM | Frequency / Timing of TCM | Intervention Points | | **R**= Real-time Control<br>**I**= Inspection<br>**H**= Hold Point<br>**W**= Witness Point |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | R | I | | | | H | W | Remarks |
| 1 | **Position of the primary and secondary steelwork in the doorways –** Deviation in the parallelism of the columns ($\Delta_x$) and deviation in the parallelism of the stanchions ($\Delta_y$) at both sides of the doorways  | Structural steelwork | Setting -out | Tolerance Agreement and Design Form | R | | Total station | Site enginee r | During erection – real time | | W | |

## 6.3.4 Part Three: Communication of Tolerance Information

### 6.3.4.1 Visualisation of Variations

The TTM Committee, especially the Tolerance Coordinator, should visualise dimensional and geometric variations applied to components. The main purpose of this step is to establish a shared understanding among project participants about the impacts of variations on KCs (explained in Appendix F). By performing this step, project participants, from operatives to managers, with any level of understanding of tolerances, can quickly grasp the following information:

- Different sources of variations applied to a component;
- Interaction of components when subjected to different sources of variations;
- Impact of accumulated variations on KCs;
- Under what circumstances KCs are not addressed.

It is difficult, if not impossible, to prescribe a completely standardised approach to conduct this step. The following suggestion is a generic, standardised approach:

- Select a KC;
- Illustrate the accumulated induced variations affecting the selected KC;
- Illustrate the inherent variations when added to the induced variations and affecting the selected KC;
- Illustrate the tolerance zone (i.e., an area within which lower and higher limits of the accumulated variations fall);
- Illustrate the interaction of components with each other due to the sources of variations influencing the selected KC.

Note that the proposed approach to visualise variations should be adjusted in each case and does not have to be followed strictly.

This approach is explained further in the following example. Assume that the position of the lower surface of the concrete slabs is a KC. The information collected from the prior steps is given below:

- **Construction tolerance**: ±10 mm;
- **Erection tolerance**: ±10 mm;
- **Setting-out tolerance**: ± 5 mm;
- **Accumulated tolerance for the induced source of variations**: ± 15 mm;
- **Deflection**: -20 mm;

- **Accumulated tolerance for both induced and inherent sources of variations**: -5 mm and -35 mm;
- **Position of the lower surface of the concrete slab relative to the ground floor in design**: 8000 mm;
- **Probable position of the lower surface of the concrete slab relative to the ground floor**: 7965 mm and 7995 mm.

The outcome is shown in Figure 6-75. The approach to visualise the variations affecting the KC in this example is as follows:

- The position of the lower surface of a concrete edge beam relative to the ground floor is selected as a KC;
- The accumulated induced variations affecting the selected KC is illustrated;
- The inherent variations when added to the induced variations are illustrated;
- The tolerance zone is illustrated.

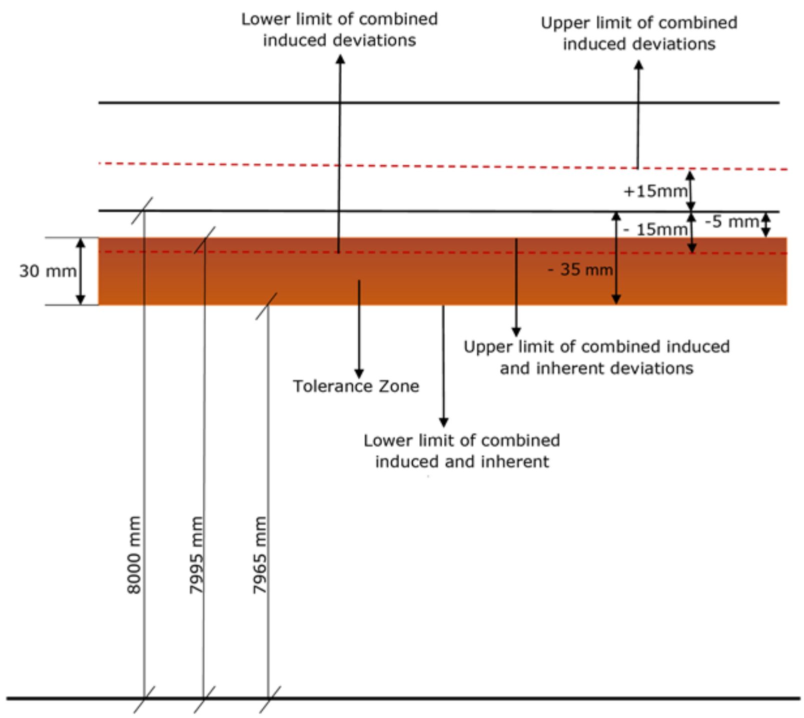



**Figure 6-75. Visualisation of sources of variations influencing the position of the lower surface of concrete slabs**

### 6.3.4.2 Incorporation of Tolerance Information in Drawings

One of the means to communicate tolerance information in TMS is through drawings. The basis of the incorporation of tolerance information into construction drawings has been explained in Section 2.8. Geometric Dimensioning and Tolerancing (GD&T) explained in section 2.12.1 is used to develop a more systematic method to incorporate tolerance information in the construction drawings.

To communicate tolerance information in TMS through drawings, first the TTM Committee should ensure that the information below is well communicated to the corresponding designers:

- The identified KCs of components and sub-assemblies;
- The permitted variations for KCs;
- Datums, if applicable.

The designers should use local or general notes on drawings to communicate the information above. Based on the type of KC, the information given in Table 6-49 should be provided in the notes.

**Table 6-49. The list of KCs and corresponding tolerance information in drawings**

| KEY CHARACTERISTICS | TOLERANCE INFORMATION NEEDED IN DRAWINGS |
|---|---|
| Straightness | The permitted deviation caused by deformation (e.g. vertical deflection) of a component. |
| Flatness | The permitted deviation of flatness that a floor surface can have. |
| Parallelism | The permitted deviation that the component must maintain from being parallel to another component.<br>The selection of a datum is essential. More specifically, one of the components should be selected as a datum. The tolerance of parallelism for the component in question is specified relative to the datum (i.e. the component which is expected to be parallel with the component in question). |
| Perpendicularity | The permitted variation that a component can have from being perpendicular to a surface or another component.<br>If the perpendicularly of a component relative to the floor surface is a KC, the use of datum is optional. If the perpendicularly of a component relative to another component is a KC, datum must be used. The main information which should be specified is how much the component can be out of the plumb relative to the datum (i.e. floor surface or another component). |
| Position | The permitted deviation that the position of a component can have from the perfect position. The perfect position is given on drawings by basic dimensions.<br>The selection of a datum is a key element. The tolerance of a position for a component is specified relative to a datum. |
| Critical dimension | The permitted deviation that the identified critical dimension can have. |

For example, Figure 6-76 shows a drawing of a doorway in an industrial building. This example has been adopted from the tolerance problem 1 in case two (explained in Section 4.2.3.1). Figure 6-76 is an extract from the drawings used in case two. In this example, the distance between the posts at the two sides of the doorway must be within the specified tolerance. Moreover, the posts must be in parallel to each other within a certain tolerance to ensure that there is an adequate distance between the posts to accommodate the door, whilst also ensuring that there are no gaps around the door. Note that even when the distance between the doors is within a certain tolerance, it does not necessarily ensure that the two sides of the doorway are in a plane. In short, the distance between the posts and parallelism of those posts are two KCs. Figure 6-76 shows how the tolerance information has been communicated in a drawing.

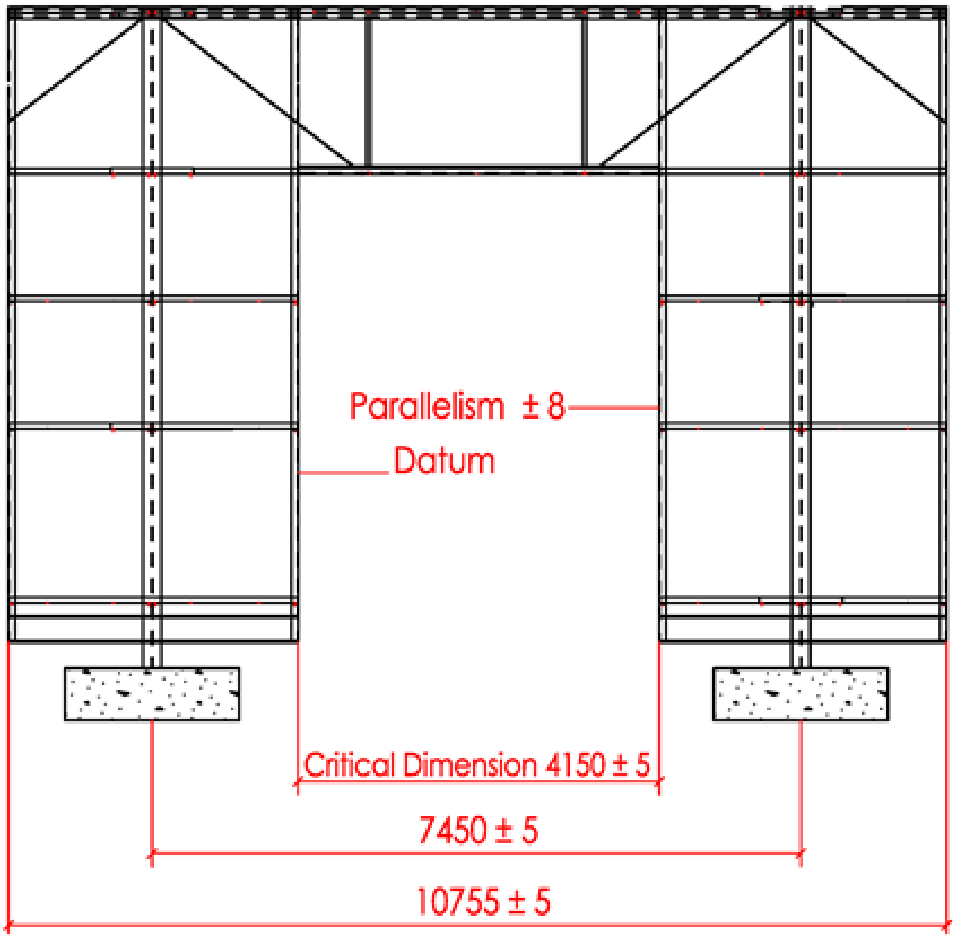



**Figure 6-76. Communication of tolerance information in a doorway in an industrial building**

#### 6.3.4.3 Creation of Unified Tolerance Specification

This step is to gather the collected tolerance information and the decisions made by the TTM Committee throughout the prior steps in a document called the Unified Tolerance Specification. The reasons behind creating such specification is: (a) to help parties, especially construction trades, understand the collected tolerance information and decisions made by using only one document containing simple language, (b) to ensure the parties are contractually responsible to follow the decisions made by the TTM Committee, especially when the decisions may differ from what has been stated in the reference documents, and (c) to make the parties aware of how components are interdependent tolerance-wise.

The Unified Tolerance Specification should be in a simple language, should only include the relevant information, and should include all the tolerance information that parties need to know (i.e. the parties should need refer to reference documents for such specifications as little as possible). The TTM Committee should begin to develop the specification from the early stages of the project and it should be gradually developed throughout the design stage. For example, the committee initially may have limited information about the loads applied to the project but as the subcontractors are procured and the designs are developed, the committee will gain a better understanding of the loads. Hence, the specification should be continuously developed with new information over time.

The specification should be available to all parties at any point during the design while it is being evolved in parallel with the design. As a result, it is envisioned that:

- The contractors can understand tolerance requirements/risks, have a better understanding of actions needed to address those requirements/risks, and then bid on the project accordingly;
- Designers will develop the design while bearing in mind the constructability and serviceability of their designs;
- Contractors can select appropriate materials, components, connections and construction methods according to the requirements/risks and the instructions contained in the specification;
- Inspectors can verify the compliance of tolerance requirements as the project moves forward on site.

It is suggested that the structure of a Unified Tolerance Specification should be as follows:

- Project overview:
  - Members of the TTM Committee;
  - Tolerance Coordinator;
- Key information in the client's brief and concept design;
- Maximum loads applied to the structure and general deflection criteria;
- Classes of tolerances;
- Tolerance Interdependency Matrix;
- Key Characteristics of components/sub-assemblies;
- Tolerance Risks Assessment;
- Visualisation of variations affecting KCs;
- Tolerance analysis;
- Load sequence;
- Tolerance Agreement and Design Form;
- Tolerance Compliance Measurement Protocol.

### *6.3.5 Part Four: The Tolerance Compliance Measurement*

#### 6.3.5.1 The Execution of the Tolerance Compliance Measurement

The Tolerance Compliance Measurement Protocol should be maintained and followed strictly throughout the construction process. This is to investigate whether the specified variations of KCs are bound within the limits.

#### 6.3.5.2 Record of Tolerance Compliance Measurement Results

The results obtained from the measurements of variations of KCs should be recorded by the surveyor in the standard form, called Tolerance Compliance Measurement Result Form and designed for this step. The form should then be given to the TTM Committee. The purpose of this step is to record the variations of a particular KC, clearly specify whether those variations are bound within the specified limits, and whether the intended function is adversely affected. Moreover, Systematic Deviation, which is the difference between the target value and the average of achieved variations, is calculated. Table 6-50 shows the standard form devised for the TCM results and Table 6-51 shows an example of a completed form.

**Table 6-50. Tolerance Compliance Measurement Results Form**

<table>
<tr><td colspan="3" rowspan="5"></td><td colspan="4">TOLERANCE COMPLIANCE MEASUREMENT RESULTS FORM</td></tr>
<tr><td>Activity</td><td colspan="3">Tolerance Management</td></tr>
<tr><td>Project / Location</td><td></td><td>Job NO.</td><td></td></tr>
<tr><td>Key Characteristic</td><td></td><td>Date</td><td></td></tr>
<tr><td>Specified Variation</td><td></td><td>Ref</td><td></td></tr>
<tr><td>Achieved Variation</td><td>Variations within limits (Y or N)</td><td>Function as intended (Y or N)</td><td colspan="4">Remarks</td></tr>
<tr><td></td><td></td><td></td><td colspan="4"></td></tr>
<tr><td colspan="3">Systematic Deviation</td><td colspan="4"></td></tr>
</table>

**Table 6-51. Completed Tolerance Compliance Measurement Results Form based on measurements in doorways of case two**

| | | | TOLERANCE COMPLIANCE MEASUREMENT RESULTS FORM | | | |
|---|---|---|---|---|---|---|
| | | | Activity | Tolerance Management | | |
| | | | Project / Location | xxx | Job NO. | xx |
| | | | Key Characteristic | Parallelism of stanchions in doorways | Date | xx |
| | | | Specified Variation | 5 mm out of parallelism | Ref | xx |
| Achieved Variation | Variations within limits (Y or N) | Function as intended (Y or N) | Remarks | | | |
| 18 mm out of parallelism | N | N | The cladding rail attached to the column in Gridline 6 was 16 mm towards north, and the cladding rail attached to the column in Gridline 7 was 2 mm towards south. | | | |
| 7 mm out of parallelism | N | Y | The cladding rail attached to the column in Gridline 7 was 3 mm was out of position towards north, and the cladding rail attached to the column in Gridline 8 was 4 mm out of position towards south. | | | |
| 9 mm out of parallelism | N | N | The cladding rail attached to column 8 was in the correct position, without being twisted, but the cladding rail attached to the column in Gridline 9 was 9 mm off towards north. | | | |
| 9 mm out of parallelism | N | N | The cladding rail attached to the column in Gridline 9 was 6 mm out of position towards north, and the cladding rail attached to the column in Gridline 10 was 3 mm out of position towards south. | | | |
| 2 mm out of parallelism | Y | Y | One end of the cladding rail attached to the column in Gridline 10 was 12 mm out of position towards south, and the cladding rail attached to the column in Gridline 11 was 10 mm out of position towards south. | | | |
| 1 mm out of parallelism | Y | Y | Minor variation. | | | |
| Systematic Deviation | | | 2.67 mm | | | |

### 6.3.6 Part Five: Learning and Documentation

The objective behind the last part of TMS, learning and documenting, it to maintain the knowledge gained after the implementation of TMS and reuse it in future projects.

#### 6.3.6.1 Creation of A3 Reports

The objective of this step is to document the information collected for each KC to be reused in forthcoming projects. The information includes the description of the KC, the risks affecting the KC, the final variations of the KC, whether the KC has been addressed, and if not, what the root causes were, how the problem was solved, and how the problem can be avoided in other projects. This is to enable the STM Committee and the TTM Committee to easily view the collected information for each KC in the next project by having only a one-page report. Note that the A3 report is not only used to document how tolerance problems were solved but it is used to record all the information associated with KCs, and whether KCs have been addressed. The most valuable information in the A3 report includes the achieved accuracy for the KCs, the identified tolerance problems and how they were resolved.

Similar to typical A3 reports, the overall flow of the A3 report devised for TMS follows the PDCA cycle. Completing the A3 reports should be the responsibility of the Tolerance Coordinator. The A3 report in TMS has six sections. Those sections and corresponding information are explained in Table 6-52.

**Table 6-52. Sections and corresponding information needed in each section**

| SECTIONS | GIVEN INFORMATION |
|---|---|
| Description of the Key Characteristic | A background of the identified KC (i.e. the type of KC, whether it applies to a component or a sub-assembly, the permissible variation on the KC, sources of variations affecting the KC, and the Characteristic Accuracy).<br>Visualisation of variations affecting the KC developed in Section 6.3.4.1. |
| Tolerance risk assessment | Risks affecting the selected KC (from the checklist for the tolerance risk assessment developed in Section 6.3.3.5).<br>The strategies to mitigate/prevent the identified tolerance risks. |
| Check/confirmation of effect | The record of tolerance compliance measurement results developed in Section 6.3.5.2.<br>Description of tolerance problem.<br>How the problem was identified (e.g. from measurements, visually, etc.).<br>Using photographs to better describe the tolerance problem. |
| Root cause analysis | The root cause type and root causes (explained in Chapter 5) which apply to the problem should be selected.<br>Whether the mitigation strategies have been effective. |
| Modification process | The complete description of the modification process and all the actions taken to solve the problem. |
| Follow-up action | More effective mitigation strategies for similar tolerance risks.<br>Any suggestions to deal with the selected KC more effectively (i.e. permissible variations). |

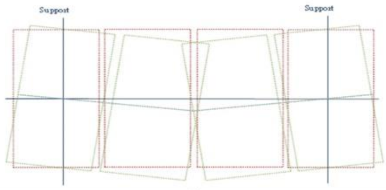
To illustrate this step further, two A3 reports are given in Table 6-53 and Table 6-54. The former is based on findings in case three and the latter is based on findings in case one.

**Table 6-53. A3 report based on findings from case three**

**Description of the Key Characteristic**

**Type**: critical dimension
**Sub-assembly**: precast cladding intermixed with glazed/curtain wall elements, beam

The envelope of the building is comprised of precast cladding intermixed with glazed/curtain wall elements. At the gable ends, pre-cast panels are positioned edge to edge. The design by the cladding subcontractor is to maintain a consistent 20 mm gap between the panels. Such clearance is influenced by three parameters, namely: (a) the rotation of the panels due to vertical deflection in the edge beam, (b) fabrication tolerances, and (c) erection tolerances.




**Tolerance risk assessment**

Panels may physically clash due to: (a) the rotation of the panels due to vertical deflection in the edge beam, (b) fabrication tolerances, and (c) erection tolerances.

**Check/ confirmation of effect**

20 mm gap was achieved. Design 20 mm clearance between panels and perform tolerance analysis to ensure the 20 mm gap is maintained.

**Root-Cause Analysis**

**Modification Process**

**Follow-up Action**

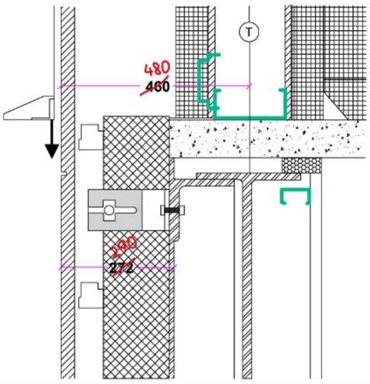
**Table 6-54. A3 report based on findings from case one**

**Description of the Key Characteristic**

**Key Characteristics**: critical dimension between the face of the stone panels and the steel column.

**Sub-assembly**: steel columns, cladding system, concrete slabs.

In the initial design devolved by the cladding subcontractor, the offset is 272 mm from the steel column to the face of the stone. This is amended by the Architect as there is a need for more room between the cladding and the steelwork to accommodate the installation. The Architect commented that the set out should be 290 mm from the face of the stone panels). This leaves the cladding system to accommodate 15 mm deviations raised from the steelwork and cladding.



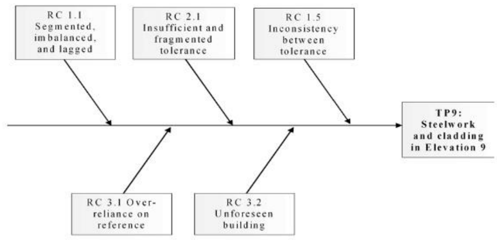

**Tolerance risk assessment**

Columns may lean into the building more than expected. As a result, the size of the clearance between the face of the stone panels and steelwork may deviate more than 15 mm. The clearance size should be smaller, as suggested by the cladding subcontractor.

**Check/ confirmation of effect**

The Architect refused to follow the design given by the cladding subcontractor. It appeared that the cladding subcontractor was correct and in Elevation 4, the steelwork leant into the building up to 30 mm at the roof level. So, a 15 mm tolerance requested by the Architect, was not enough for the cladding system.

**Root-cause Analysis**




**Modification Process**

The subcontractor had to put down all the installed stone panels and order new ones, which cost about £10K. Afterwards, the General Contractor put in new steel stiffeners and shimmed the steel, which cost about £20K. The shims used varied between 10 mm and 35 mm. In the interim, the subcontractor was unable to proceed with the work for a period of time and the General Contractor had to pay for it. The subcontractor then put the stone up. The modification cost: £30-40K.

**Follow-up action**

There should be either short clearance between the steelwork and stone panels, or appropriate connections should be provided to absorb deviations due to inclination of columns.

#### 6.3.6.2 Creation of Tolerance Manual

The aim of creating Tolerance Manuals (explained in Section 2.7.2) is to establish a guideline for implementing TMS within an organisation rather than making the implementation of TMS project-based. This step concerns the documentation of collected information, decisions made and the results of those decisions. The documentation should be referred to as an organisation-wide tolerance management standard as well as a record of the results of decisions made in projects.

A Tolerance Manual comprises of unified specifications, A3 reports and records of the Tolerance Compliance Measurement results, and it should be compiled at the end of each project by the STM Committee. The STM Committee should then provide the TTM Committee at the beginning of a project with a Tolerance Manual created in previous, similar projects. 'Similar' in this context means that the character of the project (e.g. size, type of structure, type of the cladding system, type of connections, etc.) is almost identical. The TTM Committee should then take the following actions:

- When collecting tolerance information (e.g. KCs, tolerance risks, tolerance requirements, etc.) during the implementation of TMS, the starting point should be to review the Tolerance Manuals. This will help the TTM Committee to reuse the knowledge gained from previous projects, rather than only relying on the experience of the participants involved in each project. More specifically for tolerance risks, root cause analysis of tolerance problems in other projects described in the A3 reports should be reviewed when identifying tolerance risks in similar projects;
- When assigning tolerance values to KCs, the TTM Committee should refer to the measurement results from past projects and understand what deviations will be realistically achieved, rather than only referring to reference documents and relying on the project participants. Hence, tolerance values can be assigned to KCs based on empirical data and the capability of the subcontractors to achieve them, rather than only referring to reference documents;
- When developing designs, designers can review tolerance risks and tolerance problems from previous projects and develop designs which then account for the same tolerance risks.

In short, it is envisioned that the collection of Tolerance Manuals results in creation of a repository of tolerance information that evolves over time. It is the STM

Committee’s responsibility to recognise what information in the organisation’s repository (i.e. a Tolerance Manual or a piece of information in a Tolerance Manual) is needed for the TTM Committee in a project. The utilisation of repository means that TTM Committees can collect the information quicker, the likelihood of missing a tolerance requirement/risk is lower, and the organisation can continually improve its practice of tolerance management by using the knowledge gained from previous projects. By having the repository, the likelihood that the TTM Committee would make a mistake (e.g. fail to recognise a tolerance risk) will decrease over time by not only relying on the experience of the members of the TTM Committee but by also reusing knowledge gained in previous projects.

All in all, the practice of TMS, and tolerance management in general, is envisioned to continuously improve and the PDCA cycle can be completed by reusing the knowledge gained over time through reviewing the Tolerance Manuals.

## 6.4 Summary

A summary of the steps in TMS is given in Table 6-55.

**Table 6-55. Summary of the steps in TMS**

| STEP | SUMMARY |
|---|---|
| Identification of the Key Information in the client's Brief and Concept Design | The key tolerance information in the client's brief and concept design is captured. |
| Determination of Maximum Loads Acting on the Structure and General Deflection Criteria | A high level description of (a) the loads that will be applied to the building, and (b) the resultant building movement is provided. |
| Selection of Classes of Tolerances | The class of tolerances (normal, particular, special) is determined. |
| Identification of Critical Connections and their Associated Risk Using Tolerance Interdependency Matrix | Critical connections and their associated risks are identified using the Tolerance Interdependency Matrix. The pre-determined risk of connections helps identify critical connections. |
| Identification of Critical Sub-Assemblies Using Tolerance Interdependency Network | The sub-assemblies are identified using the findings from the Tolerance Interdependency Matrix and deploying a technique called Tolerance Interdependency Network (TIN). |
| Identification of Key Characteristics of the Components/Sub-Assemblies | Key Characteristic (KC) is a feature of a component or a sub-assembly, the variation of which from the target value can result in costly modifications, damage of the functionality and a lack of safety. A list of KCs (i.e. Straightness, Flatness, Parallelism, Perpendicularity, Position, Critical Dimension), and their corresponding definitions is provided. KCs of components and sub-assemblies identified in the previous steps should be recognised. From this step onward, the focus will be on KCs only when assigning tolerances. |
| Tolerance Risk Assessment (Part One) | It is a systematic process, called Tolerance Risk Assessment, for risk identification, risk analysis and generation of responses to tolerance risks. Tolerance risks are identified by the STM committee based on their previous experiences and Tolerance Manual given by TTM committee. |
| Selection of Reference Documents to Adopt Tolerance Values for the Identified Key Characteristics | The TTM Committee determines the reference documents from which the tolerance values for the identified KCs are adopted. |
| Assignment of Tolerance Values for the Identified Key Characteristics | The TTM committee should assign tolerance values for the identified KCs based the tolerance values adopted from reference documents, experience of the members of the TTM committee, or Tolerance Manuals. |
| Determination of Characteristic Accuracy | Variations from the specified tolerances is inevitable. The TTM committee should determine the Characteristic Accuracy for each of the identified KCs. The Characteristic Accuracy for each KC can be found from either reference documents, experience of the members of the TTM committee, or Tolerance Manuals. |
| Evaluation of Combined Deviations (Tolerance Analysis) | The accumulation of deviations in sub-assemblies should be evaluated, especially by the tolerance coordinator, to ensure that deviations of the identified KCs do not exceed the specified limits. For this purpose, the root sum square (RSS) method is used for calculating the total deviations due to manufacturing/construction/fabrication tolerances. Deviations due to inherent deviations are added arithmetically to the finding from the RSS using the worst-case method. |
| Tolerance Risk Assessment (Part Two) | In the second part of the risk assessment, the TTM Committee should find appropriate strategies to mitigate the identified tolerance risks. The strategies include risk avoidance/mitigation (e.g. selection of appropriate connections, selection of an appropriate load sequence, selection of an appropriate load sequence), risk insurance, and risk acceptance. |

**Table 6-55 Continued**

| STEP | SUMMARY |
|---|---|
| Completion of the Tolerance Agreement and Design Form | The TMM Committee should start completing the Tolerance Agreement and Design Form. The main purpose of completing this form is to (a) specify the permitted variations of the identified KCs, (b) define the contractual relationships of the parties involved in the design of components, (c) communicate the identified KCs, the permitted variations of each KC, the responsible to design the components influencing the variations of the KCs. |
| Completion of the Tolerance Compliance Measurement Protocol | A document called Tolerance Compliance Measurement Protocol is completed by the TTM Committee in order to plan the verification of the specified limits for KCs. |
| Visualisation of Variations | The Tolerance Coordinator should visualise dimensional and geometric variations applied to components. A generic approach is developed to perform such visualisation. |
| Incorporation of Tolerance Information in Drawings | The TTM committee should communicate the tolerance information (i.e. the identified KCS of components/ sub-assemblies, the permitted variations for KCs, the location of datums) through local or general notes. |
| The Execution of the Tolerance Compliance Measurement | The Tolerance Compliance Protocol should be maintained throughout construction to ensure the specified tolerances for KCs are bound within the limits. |
| Record of Tolerance Compliance Measurement Results | The results obtained from Tolerance Compliance Measurement should be recorded by the surveyor in a designed standard form. |
| Creation of A3 Reports | In this step, a A3 report template is used. The information collected for each KC, including the description of the KC, the risk affecting the KC, the final variations of the KC, whether the KC is addressed, and if not, what the root-causes are, how the problem are solved, and how the problems can be avoided in similar projects. |
| Creation of Tolerance Manual | In the last step, the STM Committee compiles a document called Tolerance Manual, which is to establish a standard for implementing TMS within an organisation. A Tolerance Manual includes the unified specification, A3 reports and records of the Tolerance Compliance Measurement results. The STM Committee should provide this document compiled in previous, similar projects to the TTM Committee at the beginning of a project. |

## 6.5 Discussion

It is envisaged that TMS is being developed using standardised forms of documents and techniques on a continuous and proactive basis. By following TMS, teams are expected to realise: (a) what the optimal tolerances are, (b) what hinders parties (designers, construction trades, supply chain, and quality control teams), herein called functional groups, to achieve the specified tolerances, (c) what information is needed, (d) who is responsible for providing the information, and (e) when their input is needed. This holistic understanding is achieved by making an effective and timely dialogue between functional groups within a project and organisation. Given that a single functional group cannot have such a holistic understanding, all functional groups should work together during the design and construction and focus on critical information/actions that contribute the most to the achievement of tolerance requirements. The functional groups should each provide the information that is outlined in the TMS steps.

It can be argued that TMS should be developed to be holistic, process-driven and cross-functional. These three key terms are justified below:

**Holistic:** The approach is holistic as TMS ideally: (a) engages the insights from designers and construction trades whose components interact with each other tolerance-wise, (b) touches upon all actions needed to continually improve the practice of tolerance management, and (c) is applicable from project inception to project completion as its implementation starts from concept design and finishes with documentation of gained knowledge to be reused in next projects.

**Process-driven:** TMS is composed of methodical steps: the organisational hierarchy (i.e. Tolerance Management Board) is created; Tolerance Coordinator is designated; teams identify critical connections and sub-assemblies; highest tolerance risks are identified; the relationship between components in sub-assemblies are determined; the combined impact of deviations is analysed; the most appropriate assembly process is selected; optimal tolerance measurement compliance is chosen; and all findings and measurement results are documented. In the next rounds of implementing TMS, the information documented in the previous similar projects will be reused throughout the steps in TMS.

**Cross-functional:** TMS is devised to be a cross-functional systemthat requires involvement of all parties that have influence over the dimensional and geometric accuracy of components and assemblies.

TMS puts the pieces of the puzzle next to each other to ensure that essential tolerance information (e.g. tolerance risks and requirements) is captured and communicated in a consistent language. Hence, it is important to follow the steps as suggested to not interrupt the flow of information in TMS (e.g. by not capturing the information needed in latter steps) and impair establishing a shared understanding of tolerance risks among participants.

All in all, a thorough application of TMS is expected to help the industry, especially general contractors, continually improve its capability to: (a) identify tolerance requirements/risks early at the pre-construction stage, and (b) find solutions that will be timely, effective and efficient to prevent/mitigate tolerance risks and obtain tolerance requirements. This process should lead to fewer defects, fewer by-products, less scrap, less rework, less adversarial impacts on cost and schedule of projects and, overall, a leaner construction process.

# CHAPTER 7: **EVALUATION**

The use of focus groups for the evaluation in Design Science Research was explained in Chapter 3. In this research, two focus groups were conducted in order to evaluate the artefact (i.e. Tolerance Management System), proposed in this thesis. The purpose of the evaluation was twofold: (a) to reveal whether the proposed artefact can fulfil its aim (in other words, whether it can pre-empt costly and time-consuming tolerance-related problems at stages preceding the time of assembly on site), and (b) to improve the framework in the sense that it becomes closer to what the industry needs. In this Chapter, the outcomes of focus groups and the refined version of TMS are presented. This Chapter was to fulfil the third objective of this research, which was to evaluate the proposed solution.

## 7.1 Focus Groups Outcomes

A summary of the discussions, comments, enquiries and recommendations made after each question during the focus group meetings is given below.

***Is the framework useful in a sense that it will lead to an improved tolerance management in construction (i.e. prevent tolerance problems proactively)?***

All the participants replied "yes" (FG1, FG2). The framework is useful in a sense that it gives a prompt for what contractors have to look for. Also, following TMS ensures that designers are aware of tolerance requirements and risks when designing connections and sub-assemblies (FG2). There are contributions to knowledge and practice in each step of TMS which can potentially improve tolerance management in construction (FG1). It was acknowledged that the most useful documents in TMS are the Tolerance Interdependency Matrix (FG1, FG2) and Tolerance Risk Assessment (FG2). It was suggested that the Tolerance Interdependency Matrix should be developed further to include more details (FG1).

***Is the framework adaptable for steel and concrete framed building construction projects? Is the framework generalisable to other types of projects (e.g. timber framed construction, modular construction)?***

The participants agreed that TMS is generalisable to any form of construction (as roads, bridges, highways and sewage projects) and should not be limited only to steel and concrete frame building construction (FG1, FG2). It was mentioned that "this thesis should be considered as a guide for tolerance management for the whole industry" (FG1). The scope of TMS can be extended by undertaking more research on determining what steps are needed for each type of construction, adding more technical aspects (e.g. finding more Key Characteristics, identifying tolerance interdependencies between components), and adding more techniques (e.g. quality control during the manufacturing process) (FG1). Some of the steps should probably be developed further for more complex projects (e.g. industrial plant) but some other steps will stay the same (FG1). For example, the language developed to communicate Key Characteristics, and the steps related to learning and documentation seem to be applicable in any type of construction (FG1). Overall, there is no need to make a dramatic change in TMS to generalise it (FG1, FG2).

***In terms of clarity and simplicity, is the framework easy to implement?***

The participants replied that TMS is clear and simple (FG1, FG2). They argued that although TMS seems easy and simple, there are other hindrances such as sustaining the implementation of TMS throughout the project and motivating practitioners to follow all steps and complete all of the forms (FG1). TMS should be simplified more to make it more marketable (FG1). The participants said that "we would look to integrate steps of TMS into our existing quality management systems rather than having a standalone procedure for tolerance management" (FG2). The quality plan should have a specific section on tolerances. Otherwise, having existing quality control documents and the TMS's documents makes the quality control more difficult (FG2).

***Does the proposed framework have the potential to be accepted by practitioners and be used in the industry?***

It was agreed amongst the participants that TMS can certainly be adopted easily (FG1, FG2). If the economic advantages are highlighted, then there is a higher chance that TMS will be accepted by practitioners (FG1). The participants in the second focus group indicated that "yes… there is nothing that you have said today that we should not be doing as a standard process. If we do not get [the work] right the first time, it costs us money" (FG2). Participants in FG1 suggested that large clients should be approached. If the clients are willing to implement TMS, then contractors will definitely follow it. The other alternative would be to approach organisations developing reference documents to incorporate TMS in their reference documents (FG1).

However, there are some terms and techniques that may be difficult to understand for practitioners and they should be made more "construction-friendly" (FG2). The participants recommended to "tone down some of the academic language so it is in layman's terms …, [and then TMS] would probably be more readily accepted" (FG2). An example would be terms such as Systematic Deviation, which require basic mathematical knowledge to be understood (FG2).

***Does the time and cost needed to implement the framework outweigh the costs saved due to eliminated rework, delays and poor quality?***

The views on this question were different in FG1 and FG2.

- It was discussed in FG1 that the time and cost needed to implement the framework depends on the type of the project. It is useful to fully implement TMS in projects with a high cost. In such projects, it is justifiable to have an independent role as the tolerance coordinator to ensure the proper implementation of TMS;
- In FG2, the participants acknowledged that "we need to be more concerned with tolerances. It is an issue across the industry." Tolerance problems are costly and they may cost contractors remarkably more than avoiding them proactively. An example of a tolerance problem in a project was given and it was argued that despite the contractor having spent over a million pound to solve a tolerance problem, the building was still defective and was not of the quality intended. Also, fixing those problems can be greatly laborious and such problems can damage the reputation of contractors, for example, when there is water leakage in the ceiling. One participant concluded that if contractors can integrate TMS into their existing systems, then implementing TMS should not take any more time, as having a few more documents is not a major issue.

In short, the participants of FG1 believed that the implementation of TMS is more justifiable in projects with higher contract value. Conversely, the participants of FG2 supported the implementation of TMS in all projects because fixing tolerance problems can be very costly, time-consuming and laborious, whereas the implementation of TMS does not require significant cost and time.

***Are the documents and techniques developed in the framework applicable for the practice of construction companies?***

The participants believed that it would not be difficult to implement TMS (FG1, FG2). In FG2, it was acknowledged that documents and techniques can be readily integrated into practice. After reviewing all techniques and documents once again, the participants in FG2 continued that among all, the pre-defined key information in the client's brief and concept design, the Tolerance Interdependency Matrix, the Tolerance Risk Assessment, the Tolerance Agreement and Design Form, the Tolerance Compliance Measurement Protocol, and the Record of Tolerance Compliance Measurement Results can be used in practice immediately. They continued that the Tolerance Interdependency Matrix should be used at the tender stage because it highlights the areas which the general contractor should be prioritising for accounting and cost management purposes; the Tolerance Agreement and Design Form should be integrated into the existing design management plan, the Compliance Measurement Protocol and the Record of Tolerance Compliance Measurement Results should be integrated into the existing quality plan (FG2).

***Is the underlying logic behind the flow of information (i.e. order of steps) suitable?***

It was acknowledged that the flow of information is logical (FG1, FG2). It starts with identifying risks and requirements, followed by planning in detail, communication, checking and ultimately the feedback process (FG2).

***Does the proposed organisational design in TMS fit with the existing organisational hierarchy of your company and typical organisational hierarchy of construction companies in general?***

The participants did not support having the TTM and STM committees in typical construction projects (FG1, FG2). The term 'committee' is misleading for construction companies because those companies think that more people should be involved in projects, which means a higher cost for them (FG2). It was acknowledged that the proposed organisational hierarchy is appropriate for larger projects, such as railways (FG2).

The participants of FG2 pointed out that the role of Tolerance Coordinator, having understanding of (a) all tolerances in a project, and (b) what tolerance values can and cannot be achieved, seems reasonable. However, it is difficult to find a suitable person for the role. Architects are normally in charge of tolerance management but "[they] do not really understand it well" because they are not aware of building movement and they "do not understand how things go together on site" (FG2).

As argued in FG2, a key practical advantage of having tolerance management meetings is that the right people with the right knowledge are invited, whereas this may not be necessarily the case in the design review meetings. It was discussed that general contractors can invite preferred subcontractors to those meetings and receive their advice on what tolerances are needed and can be achieved. However, the participants pointed out two difficulties, especially in the pre-bid and pre-construction tolerance management meetings: (a) subcontractors may not be contractually bound to the project and their advice may not be robust as they do not dedicate a huge amount of resources to the project, and (b) clients may later change their mind about the design (FG2).

***Will part one of the framework lead to a full capture of tolerance requirements/risks?***

The participants stressed that the first part has to be done (FG2). Contractors currently do not identify tolerance requirements and risks at the beginning of projects and as a result, tolerance problems are recurring (FG2). Below is a summary of the discussions on the steps of part one.

Key information in the client's brief and concept design: It is the contractors' responsibility to understand tolerance requirements from the client's brief. It is useful for contractors to look for the key information listed in TMS, otherwise they may have to revisit the information when tolerance issues occur later in the project. However, the difficulty is that most clients do not have a detailed brief, especially in a Design and Build procurement system, unless it is a special project such as highways. The list of key information is more useful in a traditional procurement system where design is fully developed up front (FG2). Moreover, the listed key information in the client's brief and concept design is useful in the sense that it gives prompts for what tolerance information to look for, not only in the client's brief but also in specifications (FG2).

Classes of tolerances: The categorisation of the class of a tolerance is of significant importance because those categorisations cannot be easily understood by reading British Standards (FG2) only. When selecting a class of tolerance constructability should be taken into account (FG2).

Tolerance Interdependency Matrix: The matrix is practical to make contractors aware of connections and the risk of tolerance problems in those connections (FG2). However, the types of connections and their associated risks need further research and evidence (FG1).

Tolerance Interdependency Network: This network can at least make parties aware that the components for four or five different trades, for example, are connected tolerance-wise. However, the use of Tolerance Interdependency Network by practitioners is tedious (FG2).

Key Characteristics of the Components / Sub-Assemblies: The list of Key Characteristics helps to find characteristics that must be addressed easier (FG2).

Tolerance Risk Assessment (part one): Tolerance risks are omnipresent because "every task is followed by another task and has got a tolerance risk" (FG2). Contractors sometimes do recognise tolerance risks very early on in the project and engage designers and construction trades to mitigate those risks, however, the lack of guidelines may lead to failure of risk mitigation strategies (FG2). The Tolerance Risk Assessment "is a good method to explore tolerance risks" (FG2). It makes a reasonable assessment and breaks down tolerance risk (FG1). It may not be a comprehensive categorisation of tolerance risks but it is valuable for identifying tolerance risks (FG1).

***Will part two of the framework lead to the achievement of tolerance requirements/mitigation of tolerance risks?***

The participants summarised part two of TMS as follows: "The Tactical Tolerance Management (TTM) committee or design team identifies what the risk and requirement is and then ultimately develop a strategy to mitigate the risk and achieve the requirement" (FG2). In reply to the question, all participants replied "yes" (FG1, FG2). Below is a summary of the discussions on the steps of part two.

Assignment of Tolerance Values for the Identified Key Characteristics: It is best practice for contractors to identify Key Characteristics, prioritise them based on their risks, and start specifying tolerances for the sources of variations that impact those Key Characteristics (FG2). However, they argued that, in reality, project members normally do not define tolerance values due to their typical heavy workload and only refer to reference documents (FG2).

**Determination of Characteristic Accuracy**: When the researcher presented the concept of Characteristic Accuracy, the participants in the FG2 started to opposed it. They argued that 100% of deviations must be within the specified tolerances. By using the Characteristic Accuracy concept, subcontractors will not accept their mistakes but will rather justify that they are allowed to have, for example, one in three cases falling outside the limits. "[This concept] seems to create a grey area"

(FG2). After some discussions, the participants in FG2 stated that they understood the logic behind this concept. "The design team [or TTM committee has to look at each Key Characteristic. Then, depending on the implications of a Key Characteristic being out of tolerance, the multiplier for SD should be determined" (FG2). The participants suggested that the Characteristic Accuracy should be part of the Tolerance Risk Assessment because if not all of the cases are within the specified tolerance, contractors should know what the consequences are. It should be decided about the way in which the TTM committee deal with the risk arises from the Characteristic Accuracy concept (FG2).

**Evaluation of Combined Deviations (Tolerance Analysis)**: The evaluation of combined deviations was perceived as "understanding of what the implications [of deviations] are and the way contractors deal with… [the accumulated deviations] practically" (FG2). It was acknowledged that the information gained after the calculation can be used to develop the solution of how trades can deal with tolerances. However, the evaluation of combined deviations needs further research as there are many variables that may affect deviations of sub-assemblies (FG1).

**Tolerance Risks Assessment (part two)**: The problem with the proposed method is that the problem severity and probability are subjective and it is not clear how they are calculated (FG1).

**Tolerance Agreement and Design Form**: Contractors often tend to adopt the most lenient tolerance values from reference documents to reduce their construction costs. The Tolerance Agreement and Design Form encourages contractors to decide whether the adopted tolerance value ensures the function of the assembly, and if not, what the agreed tolerance value is (FG2).

**Tolerance Compliance Measurement Protocol**: Most site engineers do not fully understand the construction process. Their role is to use their instruments and give measurements to contractors who do not even understand what has been measured (FG2). The Compliance Measurement Protocol helps site engineers to understand what the Key Characteristics are, what the following trades are at each stage of construction, what Key Characteristics are important for each trade, and how the measurements should be performed. The general contractor can give the Tolerance Compliance Measurement Protocol to the site engineer and ask them to check the Key Characteristics, especially when the succeeding subcontractor cannot start before making sure that what has been built is within tolerance. The participants suggested that the Tolerance Compliance Measurement Protocol should be integrated into the quality plan (FG2).

***Will part three of the framework lead to the improved communication of tolerance information?***

Tolerance management to a great extent is about the communication of tolerance information between preceding and succeeding subcontractors (FG2). Below is a summary of the discussions on the steps of part three.

**Visualisation of Variations**: "It would be a useful tool for the designers to draft out [sources of variations] and make sure everything is going to fit together" (FG2). The difficulty is that practitioners need training to use this technique (FG1). It was acknowledged that this method should be integrated into BIM and then it would become more widespread (FG1, FG2).

Incorporation of Tolerance Information in Drawings: The communication of tolerance information in drawings is practical but the participants knew of only a few contractors who, to some extent, incorporate this information in their architectural and engineering drawings (FG2). It was pointed out that perhaps contractors can have separate drawings to communicate tolerance information (FG1).

**Unified Tolerance Specification**: The idea behind the Unified Tolerance Specification is to have all the information "in one place" (FG2). Having such a specification shows that "[the project participants] have thought about the information" and it aids subcontractors to fully understand the requirements (FG2).

***Will part four of the framework facilitate the verification of the compliance of the achieved deviations with the specified tolerances?***

Contractors often do not check deviations on site and rely on the follow-on trades to determine whether there is a problem (FG2). Below is a summary of the discussions on the steps of part four.

Record of Tolerance Compliance Measurement Results: The following discussions arose regarding this step:

- Following the use of Tolerance Compliance Measurement Protocol, it would be useful to provide the preceding and succeeding subcontractor with a copy of the Record of Tolerance Compliance Measurement Results. If what has been achieved is not acceptable, then the corresponding subcontractor should pay for the modification process (FG2);

- Conventionally, the site engineer gives the measurement results to the general contractor, who they expect to interpret the results. However, the general contractor is usually only concerned with whether the tolerance requirements have been achieved, and if not, whose fault it is and who will pay costs incurred due to the modification process and delay. The Record of Tolerance Compliance Measurement Results Form, as a summary document, is a reasonable solution. By referring to this document, site engineers, general contractors and subcontractors can clearly and quickly understand what the acceptable deviations are, which subcontractor's work is out of the tolerance and what the consequences are (FG2);
- The participants considered the calculation of Systematic Deviation in the form as feedback that could potentially have practical applications. However, the challenge is that such calculations may make sense in academia but not in reality for most of practitioners. They suggest that it should be presented "in layman's terms" (FG2);
- The Record of Tolerance Compliance Measurement Results should be integrated into the existing non-conformance reports (FG2).

***Will part five of the framework lead to continually improving tolerance management by reusing the knowledge gained from previous projects?***

The participants acknowledged that the A3 report and Tolerance Manuals are logical and they make sense (FG1, FG2). However, they were not sure how they could be disseminated in their business and how they would be utilised in forthcoming projects (FG1, FG2). The members of a specific project are not always aware of details in other projects, even within a same company (FG1, FG2). Hence, the documentation and learning part of TMS seems tedious at the moment (FG1, FG2). To solve this problem, they suggested that a database should be created. The design team could search for Key Characteristics in the database and they could then refer to similar cases from other projects (FG1, FG2). The database could be fostered over time and could act as a comprehensive database (FG1, FG2). The participants concluded that "we can definitely see a benefit in doing [part five of TMS] and that really is a key part of the process" (FG2). This is especially important for continuous improvement and for avoiding costly defects. Nevertheless, it needs to be complemented with a digital database (FG1, FG2).

## 7.2 Refinement of the Framework

The focus group meetings were useful for receiving constructive feedback in order to improve the designed solution. The final version of the developed framework, TMS, is formulated under the light of the received feedback. A summary of the recommendations and responses to those recommendations is given in Table 7-56.

**Table 7-56. Recommendations received during the focus group meetings and corresponding response**

| NO. | RECOMMENDATION | RESPONSE |
|---|---|---|
| 1 | The term 'committee' is misleading and should be changed. | Instead of the Tactical Tolerance Management Committee, the term 'project tolerance management team' is proposed. This is because the members of this team are involved at the project level.<br>Instead of the term Strategic Tolerance Management Committee, the term 'in-house tolerance management team' is proposed. This is because the members of this team are based in the General Management company and do not change. |
| 2 | Some terms (e.g. Systematic Deviations) used in TMS are difficult for practitioners to understand. | In the Tolerance Compliance Measurement Results Form, instead of the term Systematic Deviation, it is written: 'The difference between the target value and the average value (Systematic Deviation)'.<br>It is difficult to change the terms used for Key Characteristics because the flow of information in TMS would be interrupted. |
| 3 | It is difficult for practitioners to use Tolerance Interdependency Network. | By looking at the identified connections using Tolerance Interdependency Matrix, it would be easy for the project tolerance management team to recognise sub-assemblies. The team should look for the components involved in connections. By doing so, the sub-assemblies will be intuitively recognised.<br>The other response to this feedback is that further research is needed to automate the identification of those sub-assemblies. |
| 4 | The risk associated with the Characteristic Accuracy should be considered when completing the Tolerance Risk Assessment. | In the Tolerance Risk Assessment, a new risk factor is added under the category of Tolerance Specification/Tolerances in Specifications. The new risk factor is 'deviations falling out of the specified limits due to Characteristic Accuracy'. |
| 5 | The Tolerance Interdependency Matrix should be developed further to include more components and more information. | Implementing TMS in a real project and collecting more data will help the author to add more information to this matrix. Hence, this recommendation is considered as a topic for future research. |
| 6 | It should be investigated what steps are needed for each type of construction. | Further research is needed to respond to this recommendation, especially through investigating each type of construction and understanding the main needs. |
| 7 | The steps of TMS should be integrated into existing systems rather than having a separate procedure for tolerance management. | It is envisaged that TMS can be integrated into the existing quality control system. Responding to this recommendation requires further investigation and is considered as a topic for future research. |
| 8 | The economic advantage of TMS should be demonstrated. | Responding to this recommendation is difficult but it is essential for the further development of TMS. Hence, this recommendation can be considered as a topic for future research. |
| 9 | The large clients should be approached to implement TMS. Also, the organisations developing reference documents should be approached to incorporate TMS in their reference documents. | This recommendation is considered for future advancement of TMS. |

## 7.3 Summary

Two focus group meetings were organised to evaluate the proposed solution for improving tolerance management in construction. Thirteen questions were asked from the participants of the focus groups. Each question represented an attribute, namely efficacy, flexibility, practicality, acceptability, efficiency and applicability. The questions were useful as they directed and stimulated discussions amongst the participants.

In general, the feedback received during the focus groups was very positive. All participants believed that the proposed solution satisfies the aim of this research and its application will lead to an improved practice of tolerance management in construction. According to the participants, the framework is clear and simple, and it is not only useful for steel and concrete framed building construction but also adaptable to other form of construction.

During the evaluation, the importance of tolerances and the potential of TMS to reduce rework and costs incurred due to the resolution of tolerance problems were highlighted. It was discussed that some of the steps of TMS can be immediately used in practice. Those steps are the pre-defined key information in the client's brief and concept design, the Tolerance Interdependency Matrix, the Tolerance Risk Assessment, the Tolerance Agreement and Design Form, the Tolerance Compliance Measurement Protocol, and the Record of Tolerance Compliance Measurement Results. There was also some scepticism. The participants believed that the TTM and STM Committees need further development; some steps (e.g. Tolerance Interdependency Network, visualization of variations) and terms (e.g. Standard Deviation) are difficult for the practitioners to understand and apply; it is not clear how the knowledge gained in previous projects can be disseminated in forthcoming projects.

The participants provided some recommendations to improve the proposed solutions. These recommendations add value to TMS and the research. Some of those recommendations were implemented and TMS was modified according to them, but most of those recommendations were considered as a guidance for future research, given the time and effort constraints of a PhD project.

As explained in Chapter 3, the design, development and evaluation of artefacts in Design Science Research are iterative and further development of TMS will be based on the same pattern. The only major difference is that in future, it will be possible to implement TMS in a pilot construction project where efficacy, flexibility, practicality, acceptability, efficiency and applicability can be evaluated. This is expected to lead to further amendments of TMS and to make TMS even closer to what is exactly needed in the industry.

# CHAPTER 8: **CONCLUSIONS**

In this chapter, an attempt is made to draw conclusions based on the findings throughout the thesis. A summary is given of how the research aim and objectives have been addressed, followed by a statement of the contributions to theory and practice in the realm of tolerance management. A discussion on the limitations of the research as well as the prospects for future research completes the chapter.

## 8.1 Review of the Fulfilment of the Research Objectives and Aim

***Objective One***

The first objective of this thesis was to obtain a comprehensive understanding of the current practice of tolerance management in the industry. The objective was framed to gain an understanding of the current practice of tolerance management, the characteristics of tolerance problems, and the root causes of tolerance problems, using literature review, interviews, observations, and document review. The findings related to this objective, presented in Chapters 2, 4 and 5, are summarised next.

The findings from cases one and two showed that a series of documents (e.g. specifications), procedures (e.g. design review meetings) and techniques (e.g. use of the adjustable connections) are used as part of the existing mechanism of tolerance management. Specifications and drawings are the main means to communicate information related to tolerances. Designers and construction trades often adopt tolerance values from reference documents (i.e. standards, industry guidance bulletins, and codes of practice) and they are often aware of permissible variations of their own components only. If a tolerance problem occurs, those construction trades attempt to solve it based on their experience, or in more severe cases, the problem is communicated to designers and then the connections and/or component have to change, or the building structure has to be stiffened.

The analysis of fifteen tolerance problems revealed that the problems had similar characteristics: they are related to the fit between components, the function of the sub-assemblies, and/or the aesthetics. Building movement, among other sources of variations, was the major reason behind the occurrence of most of the identified tolerance problems. The connection between the structure, cladding, and internal partitions is the area where most of the tolerance problems occur. Generally, throughout the observations of the fifteen tolerance problems it transpired that those problems often led to time consuming, costly and laborious rework, which can become a matter of contention between the trades onsite.

At the academic level, the topic of tolerance management comprises different fields of research, that is, the existing literature is focused on individual aspects of tolerance management (e.g. tolerance analysis, tolerances compliance verification). The literature is often limited to scattered and generic recommendations about how to improve tolerance management, and the focus of the proposed recommendations and processes is mainly concentrated on the design stage. Only two sources (i.e. American Concrete Institute, 2004; CIRIA, 1983) could be found that propose a process with a set of steps to improve tolerance management. It was shown that a holistic and pragmatic process for tolerance management starting from early project stages to its completion is currently missing.

It was argued that the reason behind the none-existence of a holistic and widely accepted solution to improve tolerance management among the research works could be the lack of an in-depth understanding of the root causes of tolerance problems. This is because solving a problem first requires identifying its root causes. Hence, a root cause analysis for the identified tolerance problems was performed during the research. A list of sixteen root causes was created, which fall into seven root cause types. The root cause types are Organisation, Tolerance Specification/Tolerances in Specifications, Regulations, Quality Control System, Work Method/Workmanship, Training, and Special Causes. Such root cause analysis provided a basis for the development of a solution towards the improvement of tolerance management.

***Objective Two***

The second objective was to develop a framework to systematically incorporate tolerances into the design and effectively control them during construction with the goal of mitigating the occurrence of tolerance problems. As presented in Chapter 6, a framework called Tolerance Management System (TMS) is proposed to achieve a consistency of (a) identifying tolerance requirements/risks, (b) obtaining tolerance requirements, (c) analysing and responding to tolerance risks, (d) communicating tolerance requirements/risks, (e) verifying the compliance of deviations with the specified limits, and (f) continually improving the performance of tolerance management. The lead approach in TMS is to minimise the complexity of the assembly process due to dimensional and geometric variations through offering simple steps. TMS has five parts and each part comprises of a set of steps. Some steps can be performed in parallel and some steps should be completed over time. The parts of TMS are: identification of tolerance requirements/risks, planning the achievement of tolerance requirements/mitigation of tolerance risks, communication of tolerance information, tolerance compliance measurement, and learning and documentation. The parts and steps have been developed based on (a) the recommendations found in the literature, and (b) the findings during the empirical studies (i.e. observed tolerance-related activities, examined documents and techniques, cross-case analysis) in order to tackle the root causes of tolerance problems. An organisational design is proposed for TMS to generally combine the expertise within the project and company to (a) implement the steps of TMS at the project level, and (b) continuously improve the practice of tolerance management at the company level. In short, TMS is a framework composed of methodical steps. Each step comprises standardised documents, methods and techniques reinforced with a particular organisational design whereby design and construction teams know exactly what tolerance information they should collect, who is responsible for providing the information, and how the responsible construction team should deliver the tolerance requirements. Two foundational elements of lean, which are process standardisation and continuous improvement, are used to develop TMS.

***Objective Three***

The third objective was to evaluate the appropriateness of TMS and explore factors that enable and impede its successful implementation. As presented in Chapter 7, two focus group meetings were held to evaluate whether the developed artefact, TMS, can satisfy the aim of this research, which is to avoid tolerance problems proactively, and then to refine TMS based on the received feedback. The participants of the first focus group consisted of academics, most of them having industrial experience, and the participants of the second focus group consisted of experienced practitioners. The feedback received during the focus group meetings were incorporated into the solution (TMS), and thus the final version of the solution was created.

One of the key aspects of the research was to propose a practical solution to improve the existing practice of tolerance management, and to ensure that the solution is simple and can be implemented at a low cost so that it would easily be adopted by practitioners. It was acknowledged during the focus group meetings that many steps of TMS can be adopted in practice immediately and, especially if TMS could be integrated into the existing quality control systems, the cost needed to implement TMS will by far be outweighed by the costs saved due to the prevention of tolerance problems. The high cost of tolerance problems and the immediate need for such a solution were highlighted and it was mentioned that no similar solution yet exists in the industry.

A number of recommendations to develop TMS further were suggested in the focus group meetings. Certain shortcomings also emerged that should be considered in the further development of TMS. Overall, it can be concluded from the focus groups that the designed artefact was successful in obtaining the research objectives.

***Review of the Fulfilment of the Research Aim***

This research aimed at developing a solution to proactively identify and prevent tolerance problems at the stages preceding assembly on site. As explained above, a systematic and holistic framework, called TMS, was developed in this research. It was acknowledged during its evaluation that TMS has the potential to be used in the industry to proactively identify, analyse and mitigate tolerance problems, and reduce the time and cost needed to fix tolerance problems on site. Therefore, the aim of this research has been satisfied.

## 8.2 Contributions to Theory and Practice

The contributions to the theory and practice of this research are presented in this section.

### *8.2.1 Contribution to Theory*

The first contribution of this research is the collection and analysis of the propositions for tolerance management not only in construction but also in manufacturing (Sections 3.4 and 3.5). The outcome of such an analysis was to understand the most important guidelines and shortcomings of the proposed processes and recommendations in the literature. Such an analysis is a contribution to theory because it can be treated as a starting point to develop more effective solutions for tolerance management in construction.

This research delved into the practice of tolerance management in two construction projects and in an engineering consultancy (Chapter 4). The tolerance-related activities and documents used in the two projects were studied to benchmark the current typical practice of tolerance management. The tolerance problems identified in those projects were analysed to better understand the main characteristics and consequences of such problems. Moreover, the practice of tolerance management in an engineering consultancy with a relatively advanced practice of tolerance management was studied to understand the best practice in the industry. As discussed in Chapter 1 and 2, most of the existing literature in the field of tolerances is based on subjective views rather than on empirical data collected on-site. Therefore, this research contributes to the existing theory by providing a better understanding of not only a typical but also an advanced practice of tolerance management in construction, as well as an understanding of the characteristics of tolerance problems that occur in building construction projects.

A root cause analysis was performed for the identified tolerance problems (Chapter 5). In that analysis, five new root causes for tolerance problems were found in comparison to the existing literature. Eventually, a comprehensive list of root causes of the identified tolerances problems was created. This gives an indication of the reasons behind the reoccurrence of tolerance problems in other projects as well. The list of root causes was a basis for developing the solutions to improve tolerance management in construction and is considered as a contribution to theory.

The developed artefact, TMS, is a framework that aligns many methods into verifiable steps, allowing practitioners in the industry to start dealing with tolerances systematically (Chapter 6). As far as it is known by the researcher, there is no other research work in the literature as holistic as TMS and as it was pointed out during the evaluation, there is no known similar solution to TMS in practice. Some of the steps of TMS are new and they have been created based on the recommendations found in the literature and findings during the empirical studies. Hence, the contribution to knowledge due to the development of TMS should be considered as a contribution to both theory and practice. Some of the contributions to knowledge of TMS are as follows: two methods (i.e. Tolerance Interdependency Matrix and Tolerance Interdependency Network) are proposed to shift the conventional focus from tolerances on components to tolerances in connections and sub-assemblies; a consistent language is used for tolerance management based on a comprehensive literature review in the construction context and by adopting new terminologies from the literature in mechanical engineering while currently there is a lack of terminology to communicate tolerance information; a method is proposed to use visual aids to communicate the impact of variations on components, connections and sub-assemblies to the project participants with any level of understanding of tolerances in a simple language while visual aids have not yet been well deployed to improve tolerance management (Da Rocha, Tezel, Talebi, & Koskela, 2018); a method is proposed to communicate tolerance information through drawings while there is no any standardised method of communication of tolerance information in drawings. It is worth mentioning that there are other steps in TMS (e.g. selection of reference documents, determination of Characteristic Accuracy, Tolerance Risk Assessment, completion of the Tolerance Compliance Measurement Protocol) that may not be unique per se but the presence of all steps in one process is innovative and unique and should be considered as contribution to knowledge.

### *8.2.2 Contribution to Practice*

The contributions of the developed artefact specifically to practice are explained next. Firstly, it was acknowledged during the evaluation that proactive tolerance management using TMS can reduce the number of defects associated with tolerances by the identification of tolerance requirements and risks early in the design stage. Specifically, tolerance risks and requirements are reflected in the design and construction process using TMS proactively. This is to reduce the remedial actions needed to solve tolerance problems during construction.

Secondly, in TMS, the project participants are guided to first understand the acceptable limit of variations influencing Key Characteristics according to the existing reference documents, and then choose the right tolerance value for sources of variations in the Tolerance Agreement and Design Form based on the experience of the participants in the Project Tolerance Management Team, and the knowledge captured from previous projects using the Tolerance Manual. Conventionally, tolerance values are often adopted from reference documents (Section 2.4.1).

Thirdly, in TMS, the focus is on the function of sub-assemblies and even though the achieved variations may comply with the specified tolerances, during the completion of the Tolerance Compliance Measurement Results, investigations take place as to whether the functional requirements are satisfied. Conventionally, the work of a contractor is accepted if deviations of a component comply with the limits adopted from reference document (Sections 3.4.1).

Finally, yet importantly, it was acknowledged during the evaluation that some of the steps of TMS can be immediately used in practice. Those steps are: the pre-defined key information in the client's brief and concept design, the Tolerance Interdependency Matrix, the Tolerance Risk Assessment, the completion of the Tolerance Agreement and Design Form, the creation of the Tolerance Compliance Measurement Protocol, and the Record of Tolerance Compliance Measurement Results Form.

## 8.3 Limitations

The empirical studies in this research consists of two construction projects (i.e. a commercial and an industrial building) and one engineering consultancy. These empirical studies gave the author an insight into the conventional and relatively advanced practice of tolerance management; the empirical data collection in the consultancy was especially useful to develop the solution proposed in this research. As explained in section 3.4.4, the data collection continued until saturation. However, given the type of buildings investigated during the empirical studies, the scope of this research is limited, whereas more empirical studies in other types of construction (e.g. off-site construction) could have resulted in expanding the scope of the solution.

The evaluation of the solution proposed in this research was based on the feedback received from two focus groups. Assembling a focus group is a common method for the evaluation in Design Science Research (as explained in Chapter 3) and the participants of the focus groups were selected carefully to ensure diverging and fruitful discussions. However, considering the time allotted for this research, it was not possible to fully implement TMS in a pilot project and to include a thorough evaluation of the solution.

## 8.4 Future Research

Recommendations for further research include the following:

- TMS should be implemented in different types of construction projects. This will help (a) to develop and amend TMS further, especially based on the type of projects, (b) to propose an implementation process for TMS according to the RIBA Plan of Work (Royal Institute of British Architects, 2013), and (c) to evaluate TMS thoroughly;

- There are many steps in the current version of TMS; not all of them may be applicable for all types of construction projects. Further research is needed to create a taxonomy in which, based on the level of complexity of projects and other criteria, certain steps would be suggested to users;
- In mechanical engineering, Geometric Dimensioning and Tolerancing (GD&T) is a symbolic language widely used to communicate both the true geometry and tolerances of components and assemblies (Krulikowski, 2012; Talebi, Koskela, & Tzortzopoulos, 2018). Further research is needed to investigate the application of GD&T in construction with the goal of developing a common language to facilitate communication of tolerance information throughout the design, construction, and inspection processes;
- Since its establishment, Building Information Modelling (BIM) has been expected to prevent tolerance problems as it does for clashes between components (Jingmond, Ågren, & Landin, 2011; Tommelein & Gholami, 2012). However, the solid modelling tools within BIM software do not contain tolerance information, but rather rough dimension of building components (e.g. windows, doors) and clearances between them (e.g. a bathroom partition from an adjoining wall) (Hardin & McCool, 2015; Sacks, Eastman, Lee, & Teicholz, 2018). Conversely, in manufacturing, the use of commercial software for computer-aided tolerancing (CAT) is common and has been successful in eliminating tolerance-related defects at stages preceding the time of assembly and during the assembly (Talebi et al., 2019). Further research is needed to explore the functions in CAT systems for tolerance management (e.g. tolerance analysis and modelling) that can be potentially adopted for BIM software systems and then to develop BIM software systems accordingly;
- Some of the steps in TMS have the potential to be automated. Further research is needed to automate TMS with the support of existing technologies (e.g., Artificial Intelligence, Terrestrial Laser Scanner).

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# APPENDIX A: REFERENCE DOCUMENTS AND TOLERANCES

After reviewing innumerable publications about tolerances in construction, the author believes that reference documents are still the richest resources to find information about tolerances in construction. Tolerance information in this context means tolerance values and methods to manage tolerances. Hence, it is important to properly understand the respective reference documents before undertaking any research in this field. This section introduces two of the reference documents, more specifically codes of practice that are most commonly used in the UK construction industry and include information about tolerance values. Other reference documents that mainly include information about tolerance management are explained in this Appendix.

## British Constructional Steelwork Association (2010)

The National Structural Steelwork Specification (NSSS) for building construction is an industry guideline created by the British Constructional Steelwork Association (2010). The guideline is to support the application of modern quality management techniques (Davison & Owens, 2012) and achieve greater uniformity in steelwork contract specifications (British Constructional Steelwork Association, 2010). This guideline can be used as part of the contract documentations to determine acceptable requirements for the fabrication and erection of steelwork structures (British Constructional Steelwork Association, 2010). These guidelines attempt to portray an as close as possible realistic practice of the industry (Davison & Owens, 2012). NSSS is aligned with the requirements of other reference documents that exist for steelwork such as BS EN 1090-1 and BS EN 1090-2 (British Constructional Steelwork Association, 2010). This document includes a detailed description of the required accuracy of fabrication, and the accepted accuracy of erected steelwork. For instance, Figure A1 shows the accepted inclination of a single storey column stated in this document.

**9.6.3.1 Inclination of single storey columns generally E**

Inclination (Δ) of top relative to base on main axes.

$\Delta = \pm h/300$

*Note: Excluding portal frames, see 9.6.3.2 and 9.6.3.3, and columns supporting crane gantries, see 9.6.13.*

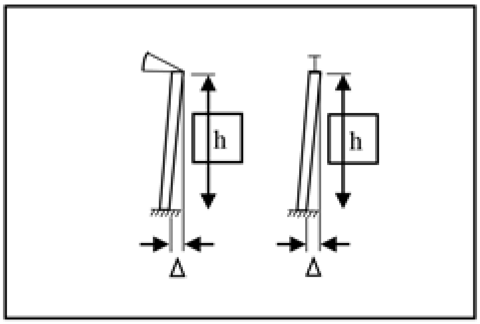
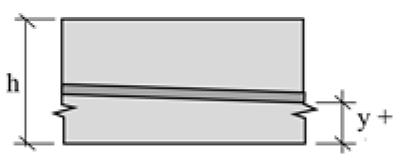



**Figure A1. Inclination of single storey columns (British Constructional Steelwork Association, 2010)**

## CONSTRUCT Concrete Structures Group (2010)

National Structural Concrete Specification (NSCS) is an industry guideline created by (CONSTRUCT Concrete Structures Group, 2010). This document provides a straightforward and definitive specification for structural concrete building construction, including in-situ concrete and precast concrete. For example, the guideline comprises the requirements of the British Standards Institution (2009a) using simple terminology. A section particularly dedicated to tolerances in the NSCS has been presented to coordinate the accuracy of concrete elements with interfacing products in typical circumstances (e.g. average temperature). For example, Figure A2 illustrates the location of reinforcement and ducts in pre-stressed elements.




- Anchorages
  Permitted location deviation Δ
  = 25 mm horizontally
  5 mm vertically
- Tendons
  Permitted deviation Δ
  Horizontally
  in beams = 0.03h (width) ≥ 5 mm ≤ 30 mm
  in slabs = 150 mm
  Vertically
  $\Delta_{(plus)}$ if h < 200 mm = +h/40
  if h > 200 mm = +15 mm
  $\Delta_{(minus)}$ all h = -10 mm
  where h for vertical section = depth in mm
  h for plan section = width in mm
  y = intended location in mm

**Figure A2. Location of reinforcement and ducts in pre-stressed elements (CONSTRUCT Concrete Structures Group, 2010)**

# APPENDIX B: INHERENT VARIATIONS

Building movement includes reversible and irreversible changes. The changes in materials due to moisture conditions are an example of reversible changes, and the settlement of the foundation is an example of irreversible changes (British Standards Institution, 1988a, 1998b). Different causes of building movement are briefly explained in Table B1.

**Table B1. Causes of inherent variations and their corresponding descriptions**

| INHERENT DEVIATIONS | DESCRIPTION |
|---|---|
| Deformation | Every material deforms when it is subject to loads. The initial deformation in components is reversible (i.e. elastic). After the forces pass a particular point, the deformation becomes irreversible (i.e. plastic) until failure (Beer, Johnston, DeWolf, & Mazurek, 2017). It is mainly important to consider the deflection that occurs after loads are applied, due to the weight of the cladding, partitions and other finishes. In fact, this type of deflection depends on the assembly sequence, particularly the critical stage in which the cladding is installed (British Standards Institution, 2009). The total deflection after the installation of cladding is due to: (a) the deflection due to the self-weight of the structure[1], (b) the deflection due to the weight of the cladding, and (c) the deflection due to the imposed loads (e.g. occupancy of the building) (Alexander, 2014). |
| Drying shrinkage and moisture movement | When concrete is poured, it is usually subject to drying conditions and accordingly drying shrinkage. Drying shrinkage can lead to deflection in beams and slabs. The flatness and levelness of concrete slabs can be distorted by the shrinkage of concrete (British Standards Institution, 2009). |
| Foundation movement | The settlement in foundations, especially differential settlement, is another important phenomenon in the context of tolerances. For example, the settlement of the foundation can adversely impact flatness and levelness of concrete surfaces (British Standards Institution, 2009). |
| Temperature and Radiation | During construction, building structures are not protected and are exposed to changes of temperature, sometimes for a long period of time (Alexander, 2014). For instance, after the concrete is laid and starts to gain strength during the first seven days or so, the differential thermal contraction between the top and bottom surface of the concrete slab can result in curling at the joints (British Standards Institution, 2009). Hence, the calculation for both contraction and expansion in the design should be taken into account (Alexander, 2014). |
| [1] The deflection of concrete slabs, due to its self-weight and weight of other components and finishes, can adversely impact on level and flatness (British Standards Institution, 2009b). When formwork is removed, the loads due to the self-weight of concrete will result in additional deflection. This type of deflection is inventible even if full back-propping is provided because nearly 70 per cent of the self-weight of a new construction is supported by the floor below. | |

# APPENDIX C: EXAMPLE FOR CHARACTERISTIC ACCURACY

To explain the concept of the Characteristic Accuracy further, the following example is given. It is considered that an in-situ concrete floor slab has a thickness in the design of 160 mm. Most slabs might have an actual thickness between 138.8 mm and 181.2 mm. The average (i.e. mean) thickness in theory would be 160 mm. but because the slabs tend to deflect when the concrete is poured, and also because of the way formworks are installed, the concrete slab most often would be thicker than the mean rather than thinner. That is, the mean (i.e. average) thickness is probably 164 mm rather than 160 mm, because table four of the British Standards Institution (1990) indicates a systematic deviation of +4.2 mm for the surface level of such floor slabs. Table C1 in this thesis shows part of the table four in the British Standards Institution (1990). The SD and systematic deviation for in-situ concrete have been marked. The question of why the thickness of such a concrete slab can vary between 138.8 and 181.2 may arise. The British Standards Institution (1990) considers that the tolerance represents the mean ±2 times the SD. Hence, the tolerance is ±2 * 10.6 or ±21.2.

**Table C1. Part of table four (Characteristic Accuracy values for construction) in (British Standards Institution, 1990)**

| ITEM OF CONSTRUCTION | | LOCATION | DATA FORM | CONSTRUCTION MATERIAL | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | BRICKWORK | | BLOCKWORK | | IN SITU CONCRETE | | PRECAST CONCRETE | | STEEL | | TIMBER | |
| | | | | $\bar{x}$ | SD | $\bar{x}$ | SD | $\bar{x}$ | SD | $\bar{x}$ | SD | $\bar{x}$ | SD | $\bar{x}$ | SD |
| T.4.3 (continued) | Suspended structural floor before laying of screed | Level (based on 2.5 m grid) Variation from the target plane of any point on the surface | e | NA | NA | NA | NA | 4.2 | 10.6 | -1.5 | 13.2 | NA | NA | - | - |
| | | Precast with *in situ* stopping<br>Level (based on 2.5 m grid) Variation from the target plane of any point on the surface | e | NA | NA | NA | NA | NA | NA | -3.0 | 14.2 | NA | NA | NA | NA |

# APPENDIX D: DESCRIPTION OF THE EXISTING PROCESS / RECOMMENDATIONS ON TOLERANCE MANAGEMENT

### *"A checklist on tolerances," (1974)*

This source is mainly focused on the specification of tolerance values at the design stage and it provides fundamental and important recommendations. It is stated that tolerances should be specified based on the following parameters:

The required accuracy to ensure stability and serviceability of the constructed building;

The process capability, that is the capability of the production team to obtain a certain level of accuracy;

The sequence of assembly process.

The specification of an appropriate tolerance is an iterative process in which a trade-off should be held between the cost of usual manufacturing and construction methods, and the cost of specifying more restrictive tolerances. Also, designers should have a good understanding of construction methods and the circumstances on site to select realistic tolerance values.

### *Construction Industry Research and Information Association (1983)*

This source recognises the problem with installing the factory-made components with relatively higher accuracy next to the traditionally executed in-situ components with relatively lower dimensional accuracy. Construction Industry Research and Information Association (CIRIA, 1983) proposes a set of steps to prevent such problems during the design and construction. Note that this source does not use the term 'tolerance' in any of the proposed steps (rather the term 'accuracy' is used) but all the steps are inherently related to tolerances, and the document can be interpreted as a proposal for tolerance management in construction. The recommended steps in (CIRIA, 1983) are as given in Table D1.

**Table D1. Recommended steps for tolerance management in (CIRIA, 1983)**

| STEP | DESCRIPTION |
|---|---|
| Step one (choosing details to avoid conflicts) | The designer should choose details which avoid conflicts between factory made components (accurate components) and site-made components (relatively inaccurate components)[1]. |
| Step two (specifying normal accuracy / special accuracy) | Normal accuracy is achieved by using typical labour, manufacturing techniques, construction methods, materials, and conditions. Tolerances for normal accuracy can be found in reference documents. Special accuracy cannot be achieved by using typical workmanship, methods, and materials. Rather, unique circumstances are required to obtain special accuracy. Special accuracy means higher cost, hence it should be required where it is essential. |
| Step three (calculating building movement) | The building movement should be determined and appropriate connections should be designed to accommodate it. |
| Step four (communicating tolerance information clearly) | Designers should be aware of the required accuracy for the installation of claddings, services, and any special equipment. Specifications should be used to effectively communicate tolerance requirements identified. In case of any special requirement, they should be detailed in the drawings. Moreover, designers should always use the permitted maximum and minimum sizes of clearances. Such clearances must allow for subsequent movements. |
| Step five (measurements) | The accuracy required in the survey process (e.g. the accuracy of measurement instrument) should be specified by the designer. This is because a survey that does not meet the accuracy requirements can result in conflict between the design team and construction trades at the construction stage. |
| [1] For instance, when a window is fitted to an opening of the same theoretical size, both the window and opening space deviate from the theoretical size. The tolerance of the window may be ±2 mm while variations in space between concrete columns cast in-situ may be ±25 mm. Such conflict should be avoided by hiding the connection between the window and the opening space. Designers should also use details which facilitate the adjustment of components within the structural frame. A common example would be slotted holes for bolts in brackets. | |

***British Standards Institution (1988a)***

The most important recommendation in this source for tolerance management is that tolerances should be specified for critical dimensions and positions only. Whether a dimension or position is critical or not is determined according to the consequences of potential tolerance problems.

***Vorlíček and Holický (1989)***

The authors in their book define tolerance management in the context of structural design and is concerned with more mathematical and engineering aspects of tolerance management and hence, the process proposed in this source is out of the scope of this thesis. However, one of the conclusions of this source is important to note: tolerance management constitutes a process and the aim of an effective tolerance management process in this source is to identify achievable tolerance requirements which ensure compliance with the identified functional requirements. More specifically, optimal tolerance values should be specified and appropriate construction techniques and measurement methods should be utilised to minimise the adversarial effects of inaccuracies on the structural stability and serviceability.

***British Standards Institution (1990)***

In this construction industry standard, a procedure for specifying tolerances and avoiding tolerance problems is recommended. The procedure is as follows:

- Identifying areas where tolerance problems are likely to occur;
- Choosing design details to avoid tolerance problems and minimise tolerance risks;
- Tolerance analysis should be performed;
- Assigning achievable and practical tolerance values based on the realistic process capability of manufacturing and construction when it is not possible to avoid tolerance problems by design;
- Providing appropriate connections to accommodate deviations;
- Communicating the tolerance requirements with project members as soon as it is feasible to ensure that all parties understand the design intends, and that they will devise appropriate countermeasures to achieve those requirements.

***Precast/Prestressed Concrete Institute (2004)***

Throughout this handbook, a set of important but scattered recommendations for managing tolerances can be found. The main recommendations are:

- The responsibility of specifying and controlling tolerances should be clearly assigned to project members;
- The discussion about tolerances should start when conceptual design is made;
- The specified tolerances should be reasonable and should not be more restrictive than limits in reference documents unless necessary;
- Connections between adjoining components should be designed while bearing in mind potential deviations;

- The responsibility to verify deviations of components with the specified tolerances should be clearly communicated with parties.

***Ballast (2007)***

The name of the book, Handbook of construction tolerances, implies that it would propose a method for tolerance management. However, the book does not explicitly propose any method for tolerance management and should be mainly considered as a compilation of reference documents on tolerances. Arguably, Ballast (2007) implicitly provides the following recommendations for tolerance management:

- Permitted limits for sources of variations have been specified in the reference documents. Designers should clearly communicate those limits in the construction documents, namely in the drawings and specifications;
- The appropriate connections should be designed to provide sufficient clearance and the capability to accommodate deviations (e.g. joints with adjustability capability), taking into account that fabrication and construction deviations and building movement usually exceeds the tolerances specified in reference documents. Also, if connections between two or more components are visible and impact the aesthetic of the building, a connection that is capable to block-out the irregularities should be designed[26];
- Three parameters should be carefully communicated through construction documents, pre-construction meetings and regular meetings during construction. The parameters are the permitted deviations, the reference documents used, and the approach to verify the compliance of the achieved accuracy with the specified tolerances.

***American Concrete Institute (2014)***

The term 'tolerance management' is not used in this document and instead 'creation of tolerance compatibility' is used. This document has been made specifically to manage tolerances when: (a) concrete elements are connected to other components and (b) the traditional design-bid-build project delivery method is adopted. Other project delivery methods may require users to follow the steps in a different order.

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[26] Examples of such variations that adversely impact the aesthetics of connections are: misalignment between two surfaces, variations in size and form of components, variations in fabrication and setting-out, and variations in positions due to building movement.

In the process proposed by American Concrete Institute (2014), it is necessary to arrange 'tolerance coordinating meetings'. Such meetings should be held before construction commences on site. The general contractor, architect/engineers, construction manager, and all subcontractors whose work will interface with concrete construction elements should attend the meeting. In these meetings, tolerance risks (e.g. the tolerance compatibility of concrete components and interfacing components) should be identified and addressed before starting the concrete construction on site. Moreover, in this document, it is recommended that an independent role should be appointed for coordinating tolerances. The role can be either the engineer or architect.

It is suggested in this document that the designers can create tolerance compatibility (i.e. manage tolerances) using the three steps as follows:

**Step one (gathering tolerance information)**: Tolerance information should be collected from appropriate reference documents, manufacturers, designers, contractors and users. Especially when standard tolerances for a component are unpublished, information should be gathered directly from contractors and manufacturers. The designers should ask manufactures, contractors and fabricators for the tolerances of adjoining components. This is to identify: (a) the tolerance requirements (i.e. plumbness, levelness, flatness, location, etc.) of constructed components to ensure the proper functioning of components and assemblies, (b) tolerance risks, including the impact of dimensional variations on the fitting process, and (c) any clearance required between components in assemblies. Moreover, this document states that there are four different tolerances: (a) tolerances on components, (b) erection tolerances, (c) envelope tolerances, and (d) assembly tolerances. In fact, it is meant that these type of tolerances should be specified. It is suggested that the designers, contractors and other responsible parties should establish a clear measurement protocol for the acceptance of the toleranced features, components and assemblies.

**Step two (evaluation of tolerance information)**: The compatibility of the specified tolerances of interfacing components should be checked. To mitigate the risk of tolerance incompatibility, additional work or rework (e.g. grinding a floor slab, applying a levelling materials) should be anticipated. The tolerance analysis should then be performed.

**Step three (generating solutions for tolerance compatibility)**: After tolerance risks are identified, appropriate strategies should be selected to mitigate those risks.

Appropriate mitigation strategies can be achieved through collaboration between project participants. Such strategies can be implemented during the design stage, procurement and construction. Some of the prevailing mitigation strategies are: (a) the use of filler materials, grout and floor levelling compound, (b) the use of adjustable and flexible connections, (c) the use of clearance, (d) the use of manufactured parts based on the as-built conditions, (e) the modification of the design of connections, and (f) the specification of more restrictive tolerances. If it is decided by the project team that tighter tolerances should be specified as an appropriate mitigation strategy, it is important that the selected restrictive tolerance must be constructible, even if at a higher cost. Otherwise, this solution as a mitigation strategy turns to be a risk to the project with significant consequences to the project cost and schedule.

# APPENDIX E:
# RISK MANAGEMENT PROCESS

The steps of risk management process are explained in this appendix.

***Risk Identification***

The process of risk management must consider all potential sources of risks and their likely consequences (Al-Bahar & Crandall, 1990). Risk identification is the first and main step of the risk management process. This process is iterative because there is always a possibility that new risks evolve as the project moves forwards (PMI, 2013). To make it more clear, this step aims at answering the following question: What can go wrong? (Haimes, 2009).

***Risk Analysis and Evaluation***

The risk analysis aims at enabling managers to reduce the level of uncertainty and to focus on risks with a high priority (PMI, 2013). This step makes the contractor aware of the consequence of not having the project exactly as it was planned (Flanagan & Norman, 1993). The estimation of the probability of the occurrence and the severity of the risk impacts are an integral part of the risk evaluation (Zavadskas, Turskis, & Tamošaitiene, 2010) and it is to a great extent subjective and depends on the management's view about the target performance and previous experiences (Tah & Carr, 2001b). Various terminologies may be used by participants to describe the likelihood of risks. The terms shown in Table E1 are commonly used to illustrate the severity of risks (Tah & Carr, 2001b).

**Table E1. Standard terms for quantifying probability (Tah & Carr, 2001b)**

| Likelihood | Probability |
|---|---|
| Very high | Expected to occur |
| High | Very likely to occur |
| Medium | Likely to occur |
| Low | Unlikely to occur |
| Very low | Very unlikely to occur |

***Response Management***

The response management process is a decision-making process (Haimes, 2009) that has two objectives: (a) eliminating the adverse impacts as much as possible, and (b) increasing control over risk (Al-Bahar & Crandall, 1990). There are four common types of responses to handle risks in the literature that are defined as follows:

**Risk avoidance**: The project team may use this response to eliminate the risk (PMI, 2013). The more moderate avoidance strategies can be identifying requirements, acquiring information, and improving communication early in the project (PMI, 2013);

**Risk mitigation**: The project team can reduce the likelihood of the occurrence or impact of an adverse risk (PMI, 2013), especially the financial severity (Al-Bahar & Crandall, 1990). Examples of mitigation actions could be conducting more tests, adopting less complex processes, choosing more reliable suppliers (PMI, 2013);

**Insurance**: Insurance is the most common strategy of dealing with risks in construction. Most contractors purchase insurance with certain deductibles for risks with high severity (Al-Bahar & Crandall, 1990);

**Acceptance**: This strategy is about acknowledging a risk when it is not possible or not cost-effective to take any action unless the risk occurs (PMI, 2013). In the acceptance strategy, contractors can establish the contingency money for the amount of time, money, or resources to deal with the risk (PMI, 2013).

In addition, the participants urged the researcher to implement TMS in a pilot project. It is expected that future evaluations on pilot projects will better demonstrate the utility of TMS and will lead to further development.

# APPENDIX F: VISUAL MANAGEMENT

In manufacturing, visual aids are deemed to be effective for the coordination of tolerances amongst design teams and the adoption of realistic tolerance values (Da Rocha et al., 2018; Krogstie & Martinsen, 2013). Visual Management (VM) is part of the Principle 7 of the Toyota Production System, which is to "use visual control so no problems are hidden" (Liker, 2004, p. 284). The objective of using VM is to make communication attractive and simple (Ho, 1993). VM simplifies the distribution of information amongst individuals and teams, and unifies information sharing within an organisation (Tezel, Koskela, & Tzortzopoulos, 2016). VM supports the design in terms of facilitating coordination between design teams (Seuring & Gold, 2012). This is because VM establishes a shared understanding of different interpretations of requirements raised by designers (Koskela, Tezel, & Tzortzopoulos, 2018).

However, a review of the literature reveals that VM has not yet been well deployed to improve tolerance management (Da Rocha et al., 2018). The first attempt towards the utilisation of visual aids for tolerance management in the literature is probably by Eldridge and Britain (1974) who proposed a method that was meant to be used to: (a) coordinate tolerances between component manufacturers, designers and contractors, and (b) simplify complicated tolerance analysis procedures. In this method, the deviation of components in an assembly could be visualised to determine adequate clearance between components and avoid conflicts. Most recently, Milberg and Tommelein (2004) proposed a method that is termed 'tolerance mapping'. In this method, the principles of a manufacturing tool are used to visualise the impact of the deviation of components on the joints between components. Tolerance mapping has been proven to be an effective method for tolerance management (Milberg, 2006). However, this method seems tedious to employ because it requires a deep understanding of complicated manufacturing concepts.

All in all, VM is deemed to be useful to improve tolerance management but its potential is yet to be realised for this purpose, as contented by Da Rocha et al. (2018) and Krogstie and Martinsen (2013). Given the ability of VM to improve communication, it is envisioned that VM can be used to improve the communication of tolerance information (tolerance requirements and risks). VM can be potentially used to translate tolerance information into a simple language. For example, the impact of sources of variations on components and sub-assemblies can be visualised. However, this topic needs further investigation.

# APPENDIX G: METHOD OF MEASUREMENTS USED FOR THE VERIFICATION OF TOLERANCE COMPLIANCE

There are various methods of measurement that can be used for measuring distances, angles, and slope and roughness of surfaces. Each of these instruments are appropriate for specific types of measurements and have varying accuracies. In Table G1, provides a list of the measurement devices that can be used for the verification of tolerance compliance, the type of measurement they can perform, and their estimated accuracy.

**Table G1. Comparative summary of the measurement instruments in construction (Ballast, 2007)**

| MEASUREMENT DEVICE | TYPE OF MEASUREMENT | ESTIMATED ACCURACY |
|---|---|---|
| Metal measuring tapes | Distance | The accuracy of a 35.5m steel tape is 6.4mm. |
| Sonic measuring devices | Distance | It is around ±3 over 15m. |
| Laser rangefinder also called Electronic Distance Measurement (EDM) | Distance | It is between ±1.5 over 200m and ±3 over 100m. |
| Carpenter's level | Angle | Their accuracy to measure angles depends on the accuracy of metal measuring tape. |
| Digital inclinometer | Angle | It is around 0.1 degrees. |
| Transit and construction lasers | Distance | It is around 1.6mm in 35.5m. |
| Electronic instruments | Floor flatness | NA |
| Laser scanners | Distance / floor flatness / angle | Their accuracy depends on the manufacturer and correctness of use. They can be very accurate, even 0.025 mm. |

# APPENDIX H: SUMMARY OF THE IDENTIFIED TOLERANCE INFORMATION IN SPECIFICATIONS OF CASE ONE

Table H1 presents a summary of the tolerance information found in the specifications of case one related to tolerances. The information has been categorised into three groups: tolerance specification, tolerance coordination, and building movement.

**Table H1. Summary of the identified tolerance information in specifications of case one**

| TITLE OF THE SPECIFICATION | DEVELOPED BY | INFORMATION RELATED TO TOLERANCE SPECIFICATION | INFORMATION RELATED TO PERFORMANCE SPECIFICATION TO ACHIEVE TOLERANCE REQUIREMENTS | INFORMATION RELATED TO TOLERANCE COORDINATION | INFORMATION RELATED TO TOLERANCE COMPLIANCE VERIFICATION | INFORMATION RELATED TO BUILDING MOVEMENT |
|---|---|---|---|---|---|---|
| Structural Steelwork | Engineering consultancy | Fabrication Tolerances<br>The maximum acceptable tolerances on fabricated items at the time of erection shall be as follows:<br>The length of strut finished for tight bearing contact: + l mm.<br>Not withstanding the above permitted fabrication tolerances, the structure shall be erected to comply with the specified erection tolerances.<br>Workmanship Tolerances<br>Lining of base plates: The maximum permissible offset in plan of a base plate from the set-out lines about both axes shall not exceed 6 mm.<br>The maximum permissible deviation from level shall not exceed 6 mm above or below the correct level. | Bolting up with Close Tolerance Bolts<br>Holes for bolts with tight tolerances shall be drilled and reamed. A bolt with tight tolerance shall be fitted in each hole reamed and tightened before the next hole is reamed. | | | |

**Table H1 Continued**

<table>
<tr><th>TITLE OF THE SPECIFICATION</th><th>DEVELOPED BY</th><th>INFORMATION RELATED TO TOLERANCE SPECIFICATION</th><th>INFORMATION RELATED TO PERFORMANCE SPECIFICATION TO ACHIEVE TOLERANCE REQUIREMENTS</th><th>INFORMATION RELATED TO TOLERANCE COORDINATION</th><th>INFORMATION RELATED TO TOLERANCE COMPLIANCE VERIFICATION</th><th>INFORMATION RELATED TO BUILDING MOVEMENT</th></tr>
<tr><td>Concrete</td><td>Engineering consultancy</td><td>Concrete Finishes<br>Foundations<br>The finish in foundations is unimportant and the structural integrity is not functionally dependent on the precise dimensions of the foundations. Therefore, the surface of the foundation may have a rough finish<br>Superstructure<br>Surfaces of all structural members should have tamped finish which complies with type B as defined in BS 8180 (6.10.3).<br>Any more stringent tolerances in particular locations will be noted on the drawings.<br>One of the locations that require tighter tolerances is the surface of slabs. Power Floated concrete slabs should comply with either of Service Regularities (SRs) as follow:
<table>
<tr><th></th><th>SR1</th><th>SR2</th><th>SR3</th></tr>
<tr><td>Max deviation under a<br>3m straight edge</td><td>3 mm</td><td>5 mm</td><td>10 mm</td></tr>
<tr><td>Max deviation from<br>Datum</td><td>±10 mm</td><td>±15 mm</td><td>±20mm</td></tr>
</table>
</td><td>Concrete Finishes (Foundations)<br>The rough finish should be achieved using sawn shuttering with any concrete top surface left vibrated.<br>Superstructure<br>To achieve such surface, shuttering made from timber or steel sheeting is suggested to be used.<br>Power float should be used for surfaces that require tighter tolerances (e.g. surfaces of slabs)</td><td></td><td></td><td>Framework<br>Formwork shall conform to the lines and levels shown on the drawings and shall be constructed as to support the pressures due to the placing of concrete without significant deflection or grout leakage and shall produce the required surface finish to the concrete.</td></tr>
</table>

**Table H1 Continued**

| TITLE OF THE SPECIFICATION | DEVELOPED BY | INFORMATION RELATED TO TOLERANCE SPECIFICATION | INFORMATION RELATED TO PERFORMANCE SPECIFICATION TO ACHIEVE TOLERANCE REQUIREMENTS | INFORMATION RELATED TO TOLERANCE COORDINATION | INFORMATION RELATED TO TOLERANCE COMPLIANCE VERIFICATION | INFORMATION RELATED TO BUILDING MOVEMENT |
|---|---|---|---|---|---|---|
| Masonry | Engineering consultancy | Accuracy of Building Walls and Tolerances<br>Great care shall be taken in setting out walls on concrete suspended slabs so that each storey-height of the wall is in line with that below. | Accuracy of Building Walls and Tolerances<br>Horizontal dimensions shall be set out with a steel tape supported throughout its length.<br>Angles should be set out by measurement or by builder's square.<br>Where buildings exceed 12m in height, optical plumbing techniques should be used to transfer setting-out grids vertically. | | Accuracy of Building Walls and Tolerances<br>Angles should be checked by instrument if they govern lines over 15m long.<br>Deviations on the site shall be measured in accordance with BS 5606: 1978: 'Accuracy in Building'. | |

**Table H1 Continued**

| TITLE OF THE SPECIFICATION | DEVELOPED BY | INFORMATION RELATED TO TOLERANCE SPECIFICATION | INFORMATION RELATED TO PERFORMANCE SPECIFICATION TO ACHIEVE TOLERANCE REQUIREMENTS | INFORMATION RELATED TO TOLERANCE COORDINATION | INFORMATION RELATED TO TOLERANCE COMPLIANCE VERIFICATION | INFORMATION RELATED TO BUILDING MOVEMENT |
|---|---|---|---|---|---|---|
| Projecting Feature Fin System | Engineering consultancy | Envelope zone tolerances<br>Floor to floor: ± 10 mm vertically<br>Lateral adjustment per floor: ± 10 mm horizontally | | Inner structure<br>Fin specialist should design and fabricate purpose made galvanised mild steel frame with integral bracing to provide support to resist building movement. | | |
| Stick Curtain Walling System | Engineering consultancy | Design and fabrication tolerances<br>Accuracy of erection<br>Line: ±2 mm of any line expressed by the framing or panels in any one storey height, and ±5 mm overall.<br>Level: ±2 mm of horizontal in any one structural bay width, and ±5 mm overall.<br>Plumb: ±2 mm of vertical in any one storey height, and ±5 mm overall.<br>Plane: ±2 mm of the principal plane in any one storey height, and ±5 mm overall. | Curtain wall adjustable support brackets<br>Movement: Brackets should accommodate movement of the curtain walling relative to the structure. | Curtain wall adjustable support brackets<br>The extent of the movement of the curtain walling should be determined by the Specialist subcontractor from data supplied directly by the client's Structural Engineer. | | |

**Table H1 Continued**

| TITLE OF THE SPECIFICATION | DEVELOPED BY | INFORMATION RELATED TO TOLERANCE SPECIFICATION | INFORMATION RELATED TO PERFORMANCE SPECIFICATION TO ACHIEVE TOLERANCE REQUIREMENTS | INFORMATION RELATED TO TOLERANCE COORDINATION | INFORMATION RELATED TO TOLERANCE COMPLIANCE VERIFICATION | INFORMATION RELATED TO BUILDING MOVEMENT |
|---|---|---|---|---|---|---|
| Natural Stone Cladding System | Engineering consultancy | | | Structural performance - permanent and imposed loads<br>*Requirement*<br>The Contractor shall determine sizes and thickness of slabs and panels; size, number and spacing of fixings; configuration and location of support systems and incorporation of accessories to ensure the cladding system will resist dead, imposed and live loads, and accommodate deflections and thermal movements without damage. | | Movement joints: Not required |

**Table H1 Continued**

| TITLE OF THE SPECIFICATION | DEVELOPED BY | INFORMATION RELATED TO TOLERANCE SPECIFICATION | INFORMATION RELATED TO PERFORMANCE SPECIFICATION TO ACHIEVE TOLERANCE REQUIREMENTS | INFORMATION RELATED TO TOLERANCE COORDINATION | INFORMATION RELATED TO TOLERANCE COMPLIANCE VERIFICATION | INFORMATION RELATED TO BUILDING MOVEMENT |
|---|---|---|---|---|---|---|
| Ventilated Rainscreen Cladding System | Engineering consultancy | Dimensional tolerances: To BS EN 1469. | | Structural performance - permanent and imposed loads<br>Deflection and movements (e.g. thermal movement) should be accommodated without damage to the cladding system. | | |
| Outline Specification | Client | | | Movement joints in gypsum board wall lining system<br>They should coincide with the movement joints in the main frame of the structure<br><br>Internal window system (demountable)<br>Deflection head required | | |

# APPENDIX I: SUMMARY OF THE IDENTIFIED TOLERANCE INFORMATION IN SPECIFICATIONS OF CASE TWO

Table I1 presents a summary of tolerance information found in the specifications of case two. The information has been categorised into three groups: tolerance specification, tolerance coordination, and building movement.

**Table I1. Summary of the identified tolerance information in specifications of case two**

<table>
<tr><th>TITLE OF THE SPECIFICATION</th><th>DEVELOPED BY</th><th>TOLERANCE SPECIFICATION</th><th>TOLERANCE COORDINATION</th><th>BUILDING MOVEMENT</th></tr>
<tr>
<td>Structural Steelwork</td>
<td>An Engineering consultant</td>
<td>Construction Tolerance<br>Construction tolerances for concrete frame construction generally shall be in accordance with the National Structural Concrete Specification for Building Construction (Fourth Edition), except where modified by the tolerances specification.<br>Construction tolerances for steel frame construction generally shall be in accordance with the National Structural Steelwork Specification for Building Construction (Fifth Edition), except where modified by the tolerances specification.<br>The tolerance class should be Class 1 (normal tolerance according to BS EN 13670)<br>The following additional tolerances shall should be applied:
<table>
<tr><th>Element</th><th>Tolerance</th></tr>
<tr><td colspan="2">Walls/columns - verticality</td></tr>
<tr><td>Max. deviation in plan position at any level relative to the intended position at the base of the building</td><td>15 mm</td></tr>
<tr><td>Max. deviation on floor level measured relative to the intended level at the reference level</td><td>10 mm</td></tr>
<tr><td colspan="2">Slab Edge</td></tr>
<tr><td>Max. deviation in level between adjacent supports</td><td>10 mm</td></tr>
</table>
</td>
<td>General Description of Building Structure<br>Provision for thermal<br>expansion must be considered in the detailing of follow on trades such as cladding and masonry.<br>Structural Design of the Cladding<br>The cladding contractor is to make due allowance for the stated accuracy of the frame construction when detailing his fixings.<br>Structural Design of the Cladding<br>The cladding design should recognise the short and long-term deflections associated with the construction technique and the cladding system needs to be flexible enough to accommodate the anticipated vertical movement during and post construction.<br>Internal Construction and Finishes<br>Internal Partition Walls<br>The contractor should consult with the manufacturer's<br>technical details to ensure that the construction is suited to the maximum partition height and/ limiting deflection.</td>
<td>General Description of Building Structure<br>The primary steel frame has been designed to accommodate thermal stresses over the full length of the building without the provision of a structural movement joint.<br>Building Movement<br>The mezzanine floor structure is designed to limit the vertical deflection to span / 360 due to the imposed load.<br>Horizontal deflections should be limited to storey height / 100.</td>
</tr>
</table>

**Table I1 Continued**

| TITLE OF THE SPECIFICATION | DEVELOPED BY | TOLERANCE SPECIFICATION | TOLERANCE COORDINATION | BUILDING MOVEMENT |
|---|---|---|---|---|
| Performance specification | Planning and Architectural Consultant | | Superstructure<br>Roof Cladding<br>Adequate provision is to be made for thermal movement of roof coverings and gutters.<br>Rooflights<br>The effects of differential thermal movement between the steel frame, gutters and siphonic pipework are to be fully considered and accounted for in the design.<br>Level Access Doors<br>Electrically operated doors should have a 25 mm thermal movement provision on door tracks.<br>Superstructure<br>Within the warehouse the clear height to the underside of haunch is to be no less than 8.0m.<br>Roof Cladding<br>The roof cladding is to be, installed at a pitch of minimum 6.0° after steelwork deflection.<br>Internal Construction and *Finishes*<br>Internal Partition Walls<br>The contractor should consult with the manufacturer's<br>technical details to ensure that the construction is suited to the maximum partition height and/ limiting deflection. | |

# APPENDIX J:
# ROOT CAUSE ANALYSIS OF THE TOLERANCE PROBLEMS IDENTIFIED IN CASES ONE

In this section, the root causes of the identified tolerance problems in cases one are investigated and two. The root causes of each problem are presented through the Fishbone diagram. In the diagrams, TP stands for tolerance problem, RC stands for root cause and RCT is equal to root cause type.

## Root Causes of Tolerance problem 1 (The Depth of Concrete Slabs)

### *Root Cause 1.2 Incomplete contract terms between the general contractor and subcontractors*

The composite steel deck-slab is designed to always be in the elastic range (The Steel Construction Institute, 1997). In this system, the top of the slab is normally finished to conform the agreed finishing tolerances (British Standards Institution, 2009a) as part of the contract with the concrete subcontractor, and consequently, the depth of concrete is greatest at the point of largest deck deflection, which is in the middle of slab span (British Standards Institution, 2009a). The increased amount of concrete should be considered in all computations. For very short spans this increased weight due to deflections is quite small, but for longer spans this weight may be significant (British Standards Institution, 2009a). However, the specification given by the metal-decking subcontractor is based on the slab poured to the constant thickness specified and any additional concrete weight as a result of deflection of the supporting structure has not been taken into account. This issue had not been effectively communicated to the general contractor and concrete subcontractor. As a result, more concrete was poured into the first floor that resulted in more deflection.

***Root Cause 1.4 Poor tolerance coordination***

The Structural designer and metal decking subcontractor did not design the structural system for any additional weight of concrete as a result of the deflection of the supporting structure. Conversely, it should be noted that according to (CONSTRUCT Concrete Structures Group, 2010), proper allowance needs to be made for the self-weight deflections when elements are struck. The responsibility for proper allowance for the self-weight deflections lies with the structural engineer and the specialist concrete subcontractor to ensure that such deflections are not excessive. However, there has been no tolerance coordination between these two parties to design appropriate countermeasures to prevent excessive deflection or mitigate the risk of such situation.

***Root Cause 1.5 Inconsistency between tolerance requirements of the project and its budget***

One of the advantages of the composite floor is that they are cheaper than other systems such as pre-cast planks. Accordingly, the general contractor decided to bid the project with metal deck and later use latex to achieve the required flatness. If the project budget had been higher, the general contractor could have used other alternatives for the floors. In that case, slabs would have had less deflection and likely tolerance problems due to deformation of concrete slabs could have been avoided.

***Root Cause 1.6 Ineffective decision-making techniques for tolerances***

The structural engineer, concrete subcontractor and metal-deck subcontractor, were involved in the project since the early stages of the project and attended the Design Meetings. However, the tolerance of the thickness of the concrete slabs had not been communicated.

***Root Cause 2.1 Insufficient and fragmented tolerance information in specifications***

The increased weight of concrete due to pouring more concrete to level the slab has not been discussed in the specification given by the metal deck subcontractor. Moreover, in this specification, it is ambiguous how much the total anticipated deflection for composite floors is.

### *Root Cause 2.2 An incomplete outline specification given by the client*

According to the outline specification developed by the client, "a decorative polished concrete floor system should be used in the Atria Space, Social Space and Circulation Spaces". However, the outline specification does not specify the structural system required to have the polished concrete as the final finish. As a result, the general contractor decided to put the price based on the cheaper and quicker working method which is composite steel deck-slab and then call upon contingency fund for remedial actions to achieve the requirements after being awarded the project.

### *Root Cause 3.1 Over-reliance on reference documents*

In (British Standards Institution, 1994), the limit in the residual deflection of the soffit of the deck (after concreting) is given as span/180 (but not more than 20 mm), which may be increased to span/130 (but not more than 30 mm) if the effects of ponding are included explicitly in the design. The metal decking subcontractor had taken the effects of ponding into account and the allowed deflection was maximally 28.5 mm in the construction stage. However, it seems to the researcher that the metal decking subcontractor had overlooked the complexity of the project and how important the deflection of the building is e.g. for aesthetic of the recessed skirting. In (British Standards Institution, 1994), it is clearly stated that if the soffit deflection is considered important, the limits should be reduced. However, the designer has only relied on the given tolerance values in the reference document and has not assigned tighter tolerances.

### *Root Cause 5.1 Incorrect types of construction methods*

One of the advantages of the composite steel deck-slab is that pouring the slabs is pretty quick and other trades can start working on the floors earlier in comparison to other methods. Because of the condensed schedule of this project and the importance of commencing the construction as soon as possible, and also higher cost of other systems explained above, the general contractor decided to use this method which increased the risk of TPs.

## Root Causes of Tolerance Problem 2
## (Flatness of Concrete Slabs Affected by Unforeseen Circumstances)

### *Root Cause Type 7 Special causes*

Raining and people's complaints to the Environment Agency of the Local Authority were unforeseen circumstances (i.e. Special Causes) which made it difficult for the concrete subcontractor to achieve the required surfaces.

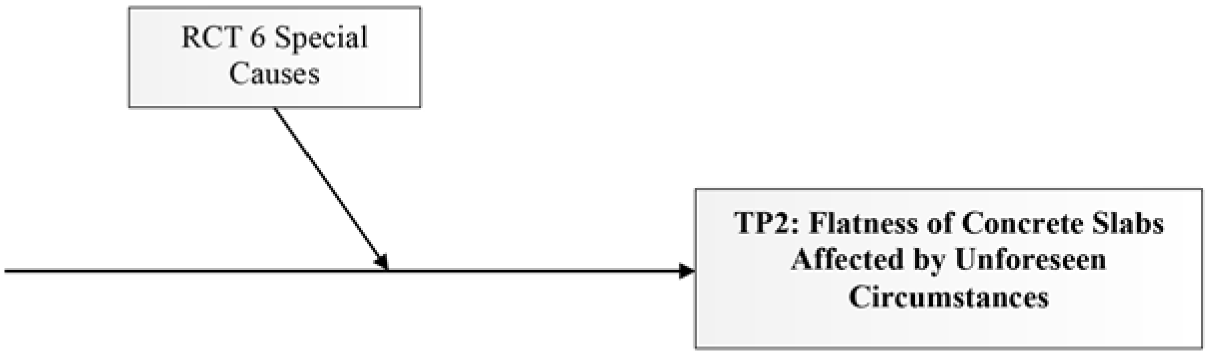


**Figure J1. Root cause of TP5 (flatness of concrete slabs affected by unforeseen circumstances)**

## Root Causes of Tolerance Problem 3
## (The Edge of Concrete Slabs and Cladding Bracket)

### *Root Cause 1.4 Poor tolerance coordination*

According to the concrete specification, the general contractor is responsible for obtaining the positions and sizes of all holes, brackets etc., from all subcontractors and should accurately set out and form them. However, due to the lack of tolerance coordination between the general contractor, cladding subcontractor and concrete subcontractor, the position of the brackets and permissible deviation in the position of the slab edge was not communicated.

### *Root Cause 2.1 Insufficient and fragmented tolerance information in specifications*

None of the specifications has considered the interfaces between the concrete elements, steel elements, and cladding system and they only revolved around tolerances of one component. Hence, the clash between the cladding bracket and concrete slabs when the concrete slabs are protruding the target surface had not been detected.

***Root Cause 3.1 Over-reliance on reference documents***

According to (CONSTRUCT Concrete Structures Group, 2010), the permitted deviation for the position of the slab edge relative to the actual position of the slab edge is ±10 mm. However, it had not been recognised that if the concrete slabs at the roof level start to deviate towards outside the building, it will conflict with the cladding brackets.

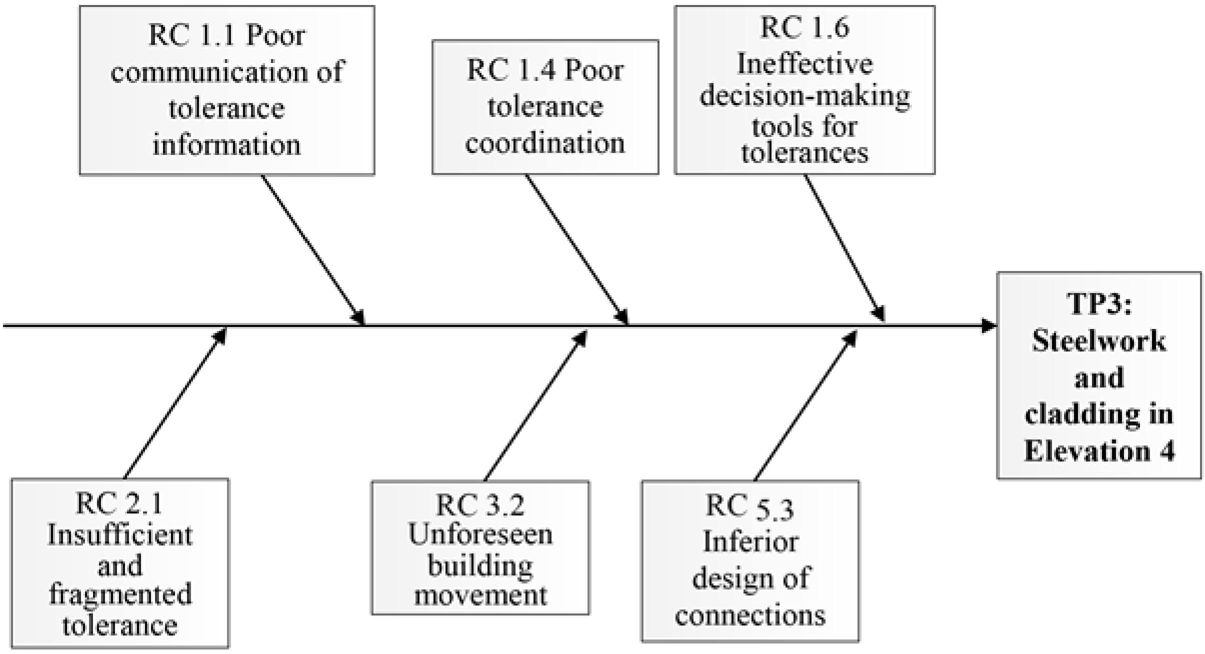


**Figure J2. Root causes of TP6 (edge of concrete slabs and cladding bracket)**

## Root Causes of Tolerance Problem 4 (Concrete Slabs and Recessed Skirting)

The Root Causes of TP2 are similar to the root causes of TP1.

## Root Causes of Tolerance Problem 5 (Concrete Slabs and Door Frame)

The Root Causes of TP3 are similar to the root causes of TP1.

## Root Causes of Tolerance Problem 6

## (Concrete Slabs and Glazed Balustrading)

The Root Causes of TP4 are similar to the root causes of TP1.

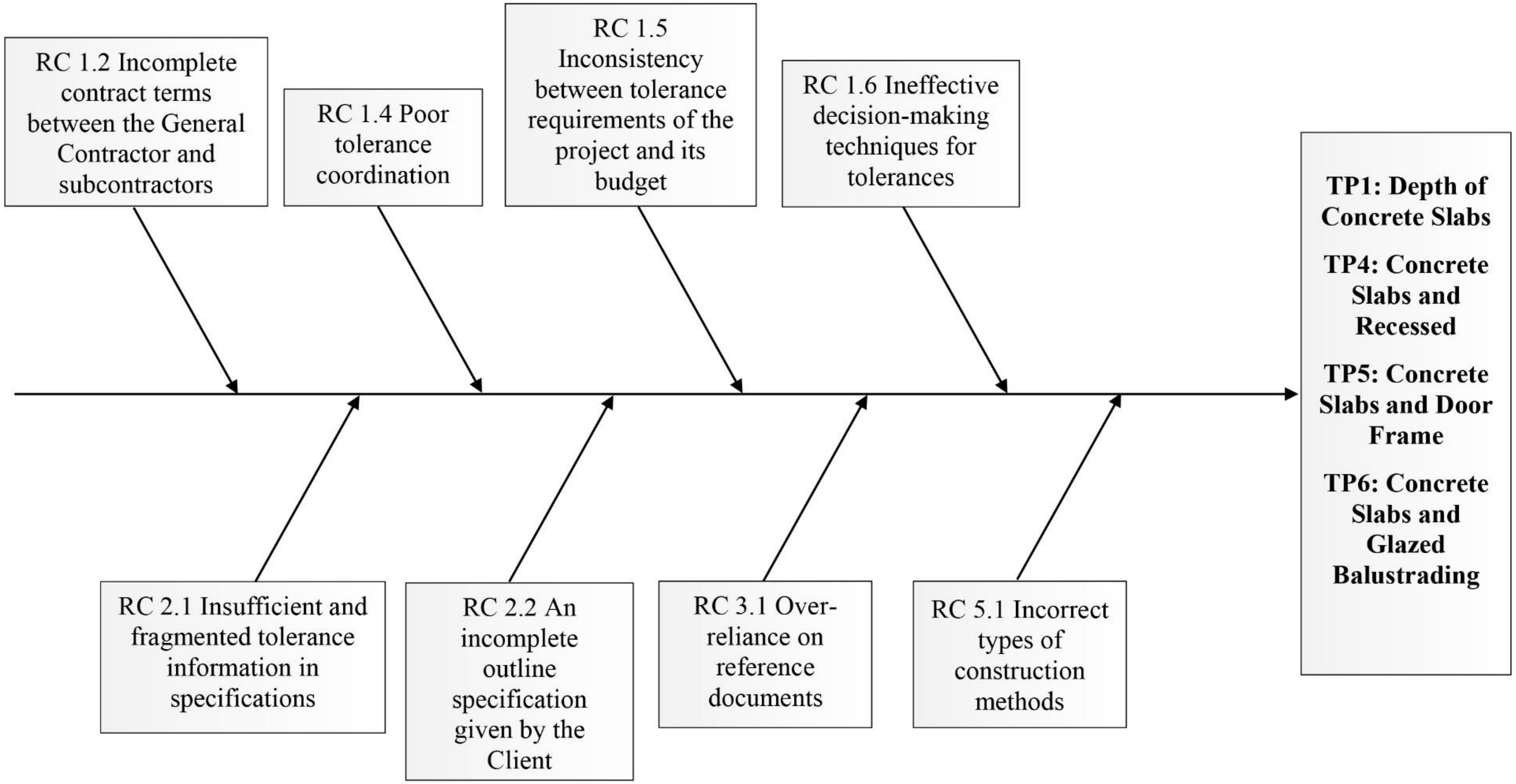


**Figure J3. Root causes of TP1 (depth of concrete slabs), TP4 (concrete slabs and recessed), TP5 (Concrete slabs and door frame) and TP6 (concrete slabs and glazed balustrading)**

## Root Causes of Tolerance Problem 7
## (Plumbness of Steel Framing Systems studs)

***Root Cause 4.1 Ineffective Quality Control documents***

None of the Quality Check Sheets included information about the permissible deviations of the plumbness of the Steel Framing Systems (SFS) studs, and how and when they should be measured. As a result, the tolerance problem with the SFS studs was recognised after they were handed over and by the cladding subcontractor when they started to build their system on the SFS studs.

***Root Cause 1.3 Deficiencies in project procurement systems***

The operatives who install the SFS studs (like operatives of partitioning subcontractors and dry liners for the internal walls) are getting paid based on the amount of the work complete dper day. This means that the quicker they work, the more money they can make. This arguably makes the operatives more prone to make mistakes and accordingly more TPs may occur which in this case resulted in the SFS studs being out of plumb.

***Root Cause 3.1 Over-reliance on reference documents***

As far as it is known, no comprehensive reference document exists, from which to adopt the tolerances of the SFS studs.

***Root Cause 5.2 poor workmanship***

Given the operatives had to complete their work as quickly as possible, they were not that much concerned about the quality of their work (according to interviewees in case one). Hence, poor workmanship was another root cause behind this TP.

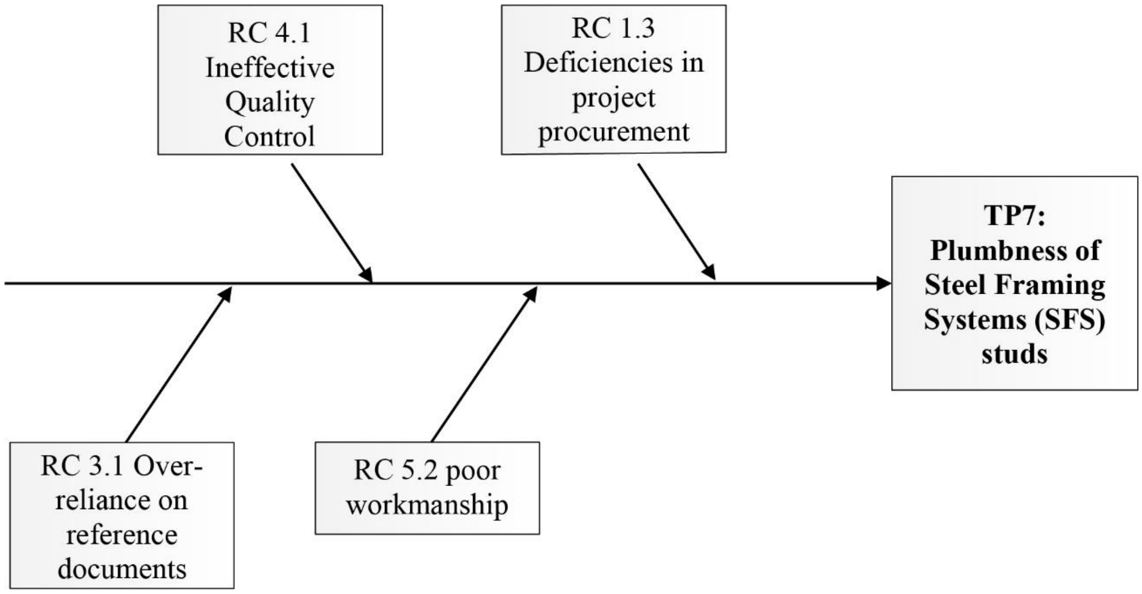


**Figure J4. Root causes of tolerance problem 7 (plumbness of Steel Framing Systems)**

## Root Causes of Tolerance Problem 8 (Steelwork and cladding in elevation 4)

***Root Cause 1.1 Poor communication of tolerance information***

There was a miscommunication between the architect and the cladding subcontractor about the required distance from the steel to the face of the stone panels. The cladding subcontractor notified the architect about the probable deformation of the steel frame and the importance of having the stone panels closer to the steel frame. This action could have enabled the cladding system to accommodate up to 35 mm deviations of the steelwork. However, the cladding subcontractor’s input into the design was when the architect had already developed the design and needed the space between the cladding and steelwork to place the building’s installations. In other words, the subcontractor’s input was lagged, and the architect was not convinced to change the design.

***Root Cause 1.4 Poor tolerance coordination***

The architect, structural engineer, steel subcontractor and cladding contractor could not conclude how deviations of the steelwork due to the erection/ setting-out/ building movement would impact the dimensional and geometric accuracy of the steelwork and then how subsequently the accuracy of the steelwork would impact the cladding system. As a result, the cladding system was not capable of accommodating the deviations.

***Root Cause 1.6 Ineffective decision-making tools for tolerances***

The cladding subcontractor notified the architect via email about the risk of the inadequate capability of the cladding to accommodate the potential deviations of the steelwork. However, this approach was not effective and the architect did not realise the importance of the reducing the clearance between the cladding system and steelwork (according to interviewees in case one).

***Root Cause 2.1 Insufficient and fragmented tolerance information in specifications***

Neither the specification of the steelwork nor the specification of the cladding, explained the interaction of these two components and how deviations of the steelwork and cladding is to be accommodated in the connection between them.

***Root Cause 3.2 Unforeseen building movement***

The steel frame, in this case, was not stiff enough due to the poor structural design (according to interviewee in case one). As a result, columns in the Elevation 4 were leaning into the building more than it was anticipated. The complexity of this project and lack of adequate information during the design made the magnitude of the building movement even more uncertain.

***Root Cause 5.3 Inferior design of connections***

The calculation of building movement, in this case, was flawed and accordingly, inappropriate connection type between the steelwork and cladding system was designed (according to interviewees in case one).

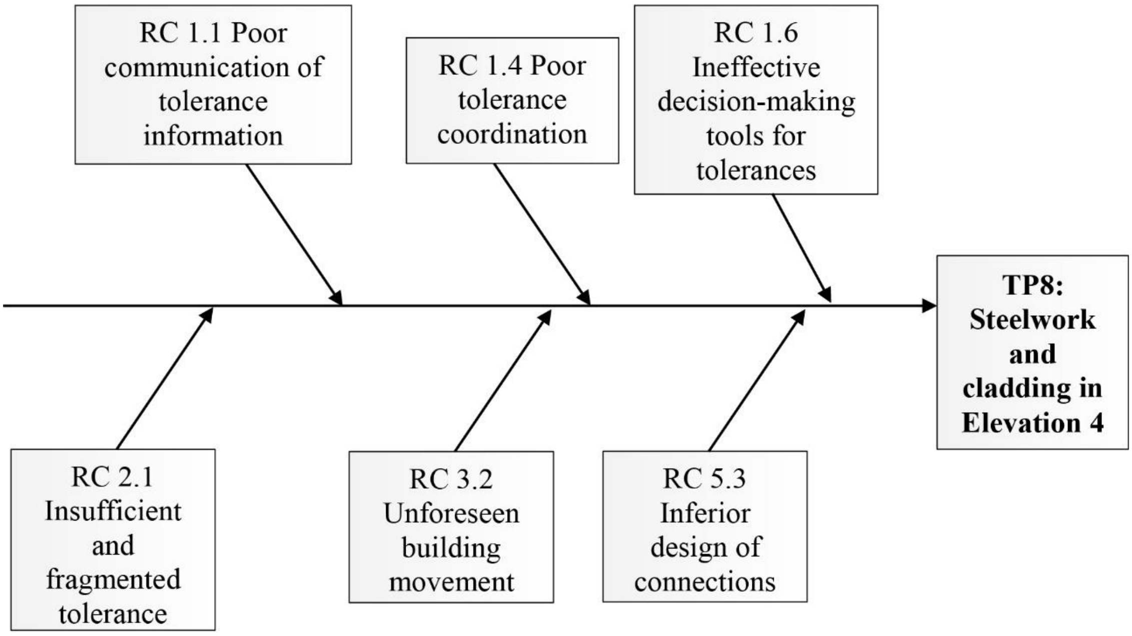


**Figure J5. Root causes of tolerance problem 8 (steelwork and cladding in Elevation 4)**

## Root Causes of Tolerance Problem 9 (Steelwork and cladding in Elevation 9)

***Root Cause 1.1 Poor communication of tolerance information***

The cladding subcontractor suggested the general contractor to provide movement joints in the connections between the steelwork and cladding system. This was to accommodate variations due to vertical deflection of the steelwork. There was a miscommunication between these two parties, and the general contractor did not perceive the importance of having movement joints, thus, denied to have it (according to interviewees in case one).

***Root Cause 2.1 Insufficient and fragmented tolerance information in specifications***

Same as RC2 in tolerance problem 8 (Steelwork and cladding in elevation 4). Moreover, in the specification for the cladding system prepared by a consultant, it is stated that "movement joints are not required". Eventually, it turned out that this instruction is incorrect.

***Root Cause 1.5 Inconsistency between tolerance requirements of the project and its budget***

Using movement joints could have avoided this tolerance problem; however, they would have been costly and exceeded the allocated budget for the cladding.

***Root Cause 3.1 Over-reliance on reference documents***

It is the same as root cause 2.1 in tolerance problem 8.

***Root Cause 3.2 Unforeseen building movement***

This problem occurred because of the exceeding deflection and twist of beams more than anticipated.

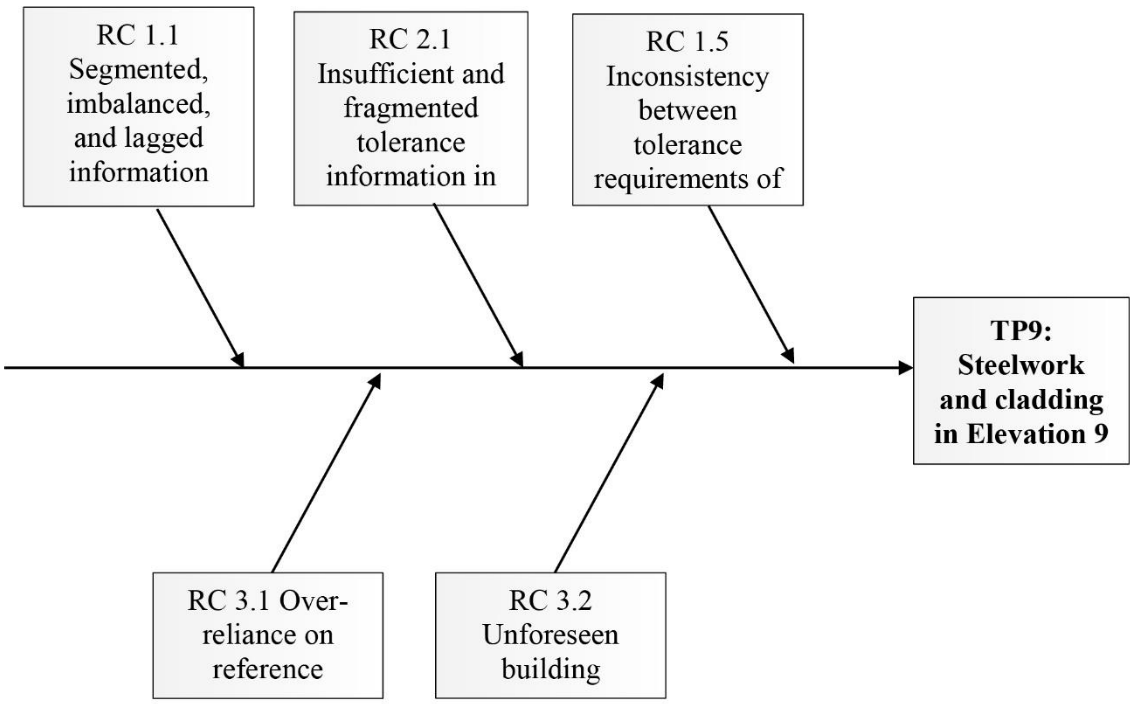


**Figure J6. Root causes of TP9 (steelwork and cladding in Elevation 9)**

## Root Causes of Tolerance Problem 10 (Steelwork and Fins)

### *Root Cause 2.1 Insufficient and fragmented tolerance information in specifications*

In the specification called 'projecting feature fin system', there is a section called 'the envelope zone tolerances' stating that any points on the steel columns are allowed to have the tolerance of ±10 mm. However, it turned out that given the complexity of this project, this tolerance was not achievable. Hence, the design of connections between the steelwork and fins had to change.

### *Root Cause 3.1 Over-reliance on reference documents*

As far as it is known, there is no comprehensive industry standard for manufacturing/ fabrication/ setting-out of fins. As a result, designers and the steel subcontractor were not aware of the tolerances of the fins until the fin subcontractor was involved. The fin subcontractor also specified incompatible tolerances with tolerances of the steelwork.

### *Root Cause 5.3 Inferior design of connections*

Given the incorrect specification of tolerances, the design of the connection between the fins and steelwork was wrong.

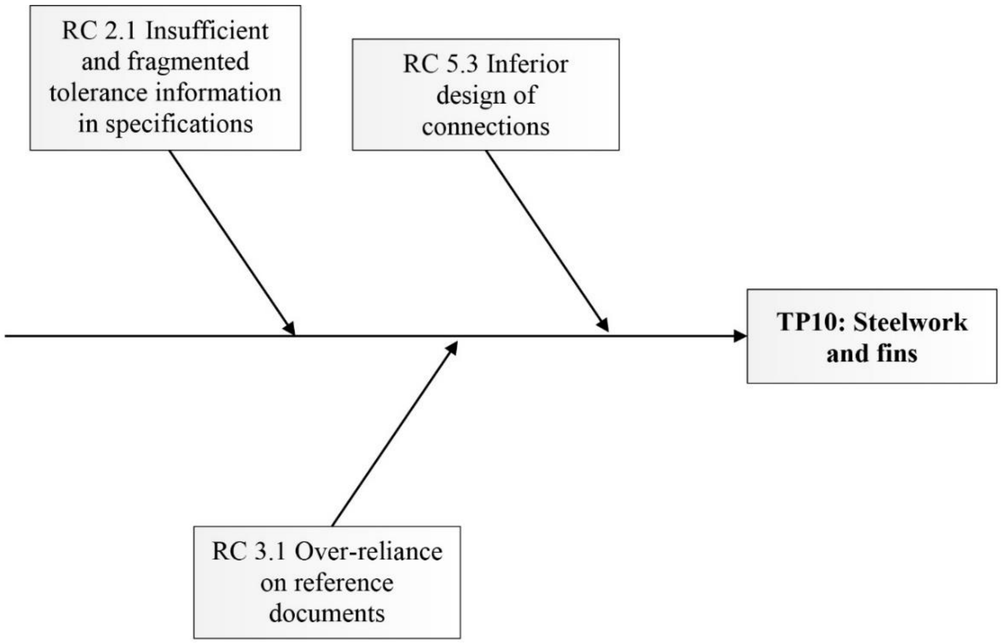


**Figure J7. Root causes of TP10 (steelwork and fins)**

# APPENDIX K:
# EXAMPLES OF CRITICAL DIMENSIONS

Table K1 presents examples of critical dimensions that are implied by the client, architect or specialised designer involved in the TTM Committee.

**Table K1. Examples of the critical dimensions specified by different parties**

| CRITICAL DIMENSIONS SPECIFIED BY | EXAMPLES |
|---|---|
| The Client | An experienced Client developing commercial buildings requests the maximum floor-to-floor height and the maximum floor area in the buildings. This is to maximise the achieved volume and area and subsequently maximise their return on investment. Therefore, the floor-to-floor height, and the width and length of the floor area are critical dimensions (British Standards Institution, 1990). |
| The Architect | When components are to be built in, the dimensions of surfaces forming the recess into which components fit, are critical (British Standards Institution, 1990). |
| The specialised designer | The height of stories and dimensions of the stair flight and stair well are critical. These dimensions are critical to receive the stair flight and avoid problems of fit (British Standards Institution, 1990).<br>A consistent clearance between the pre-cast cladding panels positioned edge to edge should be maintained to avoid clashes between the panels due to different sources of variations. The size of the clearance between the panels is a critical dimension (example from case three – explained in Section 4.4.1.6). |