Universidade do Minho
Escola de Engenharia

Muhammad Yasir

A framework for BIM-based assessment of seismic performance of existing RC buildings

European Master in
Building Information Modelling

Co-funded by the
Erasmus+ Programme
of the European Union

July 2020

Universidade do Minho
Escola de Engenharia

Muhammad Yasir

A framework for BIM-based assessment of seismic performance of existing RC buildings

BIM A+ European Master in Building Information Modelling

Master Dissertation
European Master in Building Information Modelling

Work conducted under supervision of:
Miguel Azenha
Hugo Rodrigues
Luís Guichard Castro (tutor in company)

Co-funded by the Erasmus+ Programme of the European Union

July, 2020

AUTHORSHIP RIGHTS AND CONDITIONS OF USE OF THE WORK BY THIRD PARTIES

ACKNOWLEDGEMENTS

First of all, I would like to express my gratitude to my supervisors Dr Miguel Azenha and Dr Hugo Rodrigues for their continuous support and valuable comments throughout this dissertation work. Their guidance, support and motivation helped me to complete my project within the first deadline. They were always available whenever I need any guidance regarding my dissertation. I would like to also acknowledge Luís Guichard Castro, tutor in the company, for his input and suggestions during the dissertation meetings.

I would like to further acknowledge the European Commission for the generous funding under the Erasmus Mundus scholarship to cover all my expenditures during the course of study.

STATEMENT OF INTEGRITY

I hereby declare having conducted this academic work with integrity. I confirm that I have not used plagiarism or any form of undue use of information or falsification of results along the process leading to its elaboration.

I further declare that I have fully acknowledged the Code of Ethical Conduct of the University of Minho.

Muhammad Yasir

RESUMO

Apesar do estado de elevada maturidade dos *software* BIM no contexto do projeto de estruturas, particularmente no que diz respeito à desejável interoperabilidade entre plataformas de modelação BIM e aplicações para análise/dimensionamento estrutural, há ainda lacunas técnicas importantes no contexto das trocas de informação competentes no contexto particular da análise sísmica de edifícios existentes (p.ex. em coerência com as recomendações do Eurocódigo 8 – parte 3).

Nesta dissertação pretendeu-se desenvolver uma metodologia baseada em BIM para facilitar o processo de análise sísmica de edifícios existentes em betão armado (BA), através dum conjunto de regras de modelação e ferramenta de interoperabilidade entre Autodesk Revit (plataforma de modelação BIM) e SeismoStruct (aplicação de análise estrutural). Para isso, foi utilizado um código em linguagem de programação visual desenvolvido em Dynamo. O código desenvolvido é capaz de exportar geometria, secções, propriedades de materiais, apoios e dados sobre a armadura nos pilares e vigas. Além disso, tendo em conta que as paredes de enchimento podem ter um papel relevante no contributo para o desempenho sísmico dos edifícios, a sua existência é considerada de forma explícita na metodologia aqui proposta. Esta é considerada uma contribuição importante desta metodologia, uma vez que as paredes de enchimento são normalmente ignoradas na prática corrente de avaliação de desempenho sísmico de edifícios em contexto de gabinetes de projeto.

O código de interoperabilidade proposto é capaz de analisar a informação necessária do modelo BIM e exportá-la no formato XML (*Extensible Mark-up Language*), que é reconhecido diretamente pelo *software* de análise sísmica utilizado. A análise não linear estática (i.e. análise *pushover*) é seguidamente realizada no SeismoStruct. Com base nas curvas de capacidade obtidas na análise *pushover*, e tendo em conta a análise de cenários com e sem paredes de enchimento, é possível tirar ilações sobre o comportamento sísmico dos edifícios e do papel dessas mesmas paredes. Durante a preparação da metodologia, a sua capacidade operacional foi validada num exemplo académico de um edifício regular de 4 pisos.

Finalmente, a metodologia desenvolvida foi testada e avaliada num caso de estudo baseado em edifício real, com algum grau de irregularidade. A capacidade sísmica do edifício foi aferida com análise *pushover*, com avaliação dos benefícios da consideração das paredes de enchimento. Concluiu-se que a metodologia funcionou de forma adequada, permitindo a rápida transposição de dados da plataforma de modelação BIM para o *software* de análise sísmica, permitindo, portanto que os Engenheiros de Estruturas se concentrem em tarefas de projeto/engenharia, em vez de investirem tempo em tarefas repetitivas e suscetíveis a erro na troca de informação manual entre *software*. Relevam-se as duas características especiais que se afiguram como as contribuições mais originais da metodologia desenvolvida no presente trabalho: (i) permite a consideração facilitada das paredes de enchimento na análise sísmica a partir de informação do modelo BIM, conduzindo a análises mais realistas (em oposição à tendência corrente de ignorar as paredes de enchimento); (ii) é proposto um método de modelação das armaduras baseado em informação não gráfica, facilitando a rapidez da introdução de informação no modelo BIM (e consequentemente na análise sísmica), quando comparado com a potencial alternativa de modelar todas as armaduras do edifício.

Palavras chave: BIM, desempenho sísmico, metodologia, interoperabilidade, paredes de enchimento.

ABSTRACT

Despite the mature state of BIM software in the context of structural design, particularly in concern to the desirable interoperability between BIM authoring tools and structural design software, there is still a technical/research gap in the scope of the exchange of competent data towards a seismic analysis of existing buildings (e.g. following the recommendations of Eurocode 8 – Part 3).

This dissertation aimed to develop a BIM-based framework to facilitate the process of seismic analysis of existing reinforced concrete (RC) buildings, through a streamlined set of modelling rules and interoperability between Autodesk Revit (BIM authoring tool) and SeismoStruct (seismic analysis software). This is achieved through a visual programming script developed in Dynamo. The developed script is able to export geometry, sections, material properties, supports as well as the reinforcement data for structural columns and beams. Furthermore, as infill walls can play a significant contribution to the seismic capacity of the building, they are also considered in the framework. This is considered an important contribution of this framework, as infill walls are normally ignored in the usual design office during a seismic assessment of existing buildings.

The interoperability script is able to query the necessary information from the BIM model and export it to an XML (Extensible Mark-up Language) that can be directly recognized by the seismic analysis software. The non-linear static analysis (i.e. pushover analysis) is then performed in Seismostruct. Based on the capacity curves obtained from the pushover analysis for the structure with and without infill walls, the conclusions about the effectiveness of infill wall in RC structures can be made. Upon preparation of the framework, its operational capacity was assessed on an academic-oriented example of a regular 4 storey building.

Lastly, the developed framework/script was tested and evaluated on a case study based on a real building, with some degree of irregularity. The seismic capacity of the building was evaluated using pushover analysis, with an evaluation of the beneficial effects of consideration of infill walls. It was concluded that the framework operated in a suitable manner, allowing the quick translation of data from the BIM authoring tool towards the seismic analysis software, thus permitting the structural engineers to concentrate on design tasks rather than repetitive and error-prone activities of parsing information between software. Two special features are highlighted in concern to the original contributions of the developed framework/script: (i) it allows the easy consideration of infill walls in the BIM model and hence in the seismic calculation, thus allowing more realistic assessments; (ii) a method to input reinforcement data based on non-graphical data was proposed, facilitating the quickness of the input of information to the BIM model (and hence to the seismic analysis) as compared to the alternative need to model all reinforcement bars of the building.

Keywords: BIM, Seismic assessment, Framework, Interoperability, Infill walls.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

This page is intentionally left blank

1. INTRODUCTION

1.1. Problem Overview

Building Information Modelling (BIM) involves the digital representation of a built entity and permits sharing both physical and functional information amongst all the stakeholders, throughout the entire life cycle [1]. Even though BIM processes and implementation are still mainly focused in new constructions [2], there is a strong trend for application in the context of existing buildings, which cannot yet be claimed to be generalized at all. One of such relatively unexplored fields is the seismic assessment, inherent to renovation (and eventually retrofitting) projects [3, 4]. In order to be effective in this particular context, BIM processes need to overcome several challenges including compilation and correct interpretation of existing documentation, inspection monitoring data, identification of critical data required for retrofitting, uncertainty handling and efforts required to develop the BIM model of the existing structure [5]. Despite its acknowledged importance, there is very limited research/literature on BIM-based seismic risk assessment of existing buildings Works found in the literature regarding this subject are mostly focused on matters related to 'Level of detail' [6] BIM implementation in existing buildings [7], cost optimization of seismic retrofit strategies [8], collaboration in BIM networks [9] and application of a federated model for seismic analysis [10]. No work was found to focus on the establishment of specific workflows including adequate data management and interoperability among BIM tools and seismic analysis software, towards a streamlined seismic assessment as a 'BIM use'. The seismic assessment of existing buildings is often needed (or even mandatory according to governmental rules), because of change in use, rehabilitation, constructions works or due to continuity of occupancy of a building after a moderate to a severe earthquake. Therefore, an adequate seismic assessment of an existing structure is essential to determine the eventual need to retrofit and the corresponding targets of the intervention. In the assessment of seismic vulnerability, BIM could assist by harvesting/storing important data regarding characteristics of all building elements to undertake a reliable and in-depth seismic risk assessment. Also, it can reduce the need for possibly risky and inefficient extensive physical inspections after an earthquake by managing a self-diagnosis procedure by using damage information received before and after an earthquake from structural health monitoring technologies [11].

On a broader view of collaboration in design, the traditional and conventional processes in the architecture, engineering, and construction (AEC) industry for integrating various sectors were not only costly but time-consuming as well. Moreover, the results had significant proneness to errors, as well as inconsistencies in drawings, frequently caused by inefficient collaboration and due to interoperability limitations [12]. There are many software that is being used for structural and seismic analysis of structures. But as most of these software were developed prior to the advent of widespread application of BIM methodology, many of them still have a limited capacity of interoperability at several levels [13]. The particular case of seismic risk assessment of existing buildings is one of the fields in structural engineering for which an integrated framework has not yet been set (or at least not found in the literature), involving, modelling rules/simplifications and interoperability with seismic analysis software, in a way considered readily available for the context of a structural design office. Opportunities such as the explicit consideration of infill walls in seismic assessment rise, potentially allowing more realistic seismic assessments to be made and eventually avoid unnecessary retrofitting operations.

1.2. Objectives

The main objective of this dissertation is to fill the gap identified above, within the particular context of RC buildings, through the proposal and development of a BIM-based framework to directly export relevant BIM model data from the model authoring platform (REVIT) to seismic analysis software (SeismoStruct) using a visual programming script (Dynamo), allowing a quick and effective seismic analysis using non-linear static analysis i.e. pushover analysis. To achieve the goal, this research study has the following partial objectives:

- Establishing modelling rules for both geometrical and non-geometrical data, so that the relevant information for seismic assessment can be input into the BIM model at minimal effort (with specific challenges regarding the modelling of reinforcement, for example).

- Explicitly include infill walls in both the modelling strategy and interoperability with seismic analysis software, offering an opportunity of consideration of these non-structural elements, which are often ignored, as simplification, in seismic assessment performed by RC buildings.

- Propose a specific process map to describe the practical application of the framework and demonstrate its feasibility in a practical case study based on a real structure recently assessed at the partner company of this dissertation, Newton design office.

1.3. Organization of the dissertation

Apart from the current chapter of introductory nature, this dissertation has further four chapters that are briefly described next. Chapter 2 focuses on a literature review on the seismic assessment of RC structures, as well as BIM-related aspects. The chapter includes an overview of previous research on seismic assessment, including the specificities of EC-8 part 1-3. Moreover, related to BIM-based structural design, BIM-based seismic risk analysis, sustainability and damage estimation is provided. Chapter 3 is regarding the proposal of the framework for BIM-based seismic analysis satisfying the features mentioned above. The chapter also includes the structural seismic analysis of a 4-storey RC structure performed for test and learning purpose. Then, Chapter 4 presents the application of the framework to an example based on a real RC building. It further explains the performance of the structure under lateral loads. Chapter 5 shows the conclusions of the work, summarizing the main findings of the conducted work, as well as pinpointing some perspectives for future research. Finally, Appendices are presented in which Appendix I shows the Dynamo script while Appendix II defines the user manual for the developed tool.

2. SEISMIC ASSESSMENT OF RC STRUCTURES AND BIM – OVERVIEW

2.1. Introduction

Building Information Modelling (BIM) comprises a set of processes, policies and technologies used to develop a methodology for designing a built entity, managing its data and information during the entire life cycle. BIM technology enables the creation of accurate geometrical models and attaching relevant information. BIM improves the coordination and collaboration among all the stakeholders of the project including client, architect, structural engineer, MEP engineer, consultant, contractor and operators etc.

A large number of stakeholders from the Architecture, Engineering, and Construction (AEC) industry have already adopted (or are in the process of adopting) BIM technology in their projects due to its development in the past few years. In this chapter, an overview of literature related to the seismic assessment of existent buildings and the use of BIM to support these procedures is presented. The overview starts with topics related to BIM and structural engineering, shifting then focus on aspects related to the seismic analysis of existing buildings. A brief overview of EC8-3, N2 method for pushover analysis, response spectrum, and the literature regarding the seismic analysis is explained. Moreover, an overview of previous studies related to BIM-based seismic analysis, sustainability and damage estimation is provided.

2.2. BIM in structural design

The concept of BIM is enhancing the productivity of work at the AEC (Architecture, Engineering, and Construction) industry. The BIM system is offering multi-dimensional solutions which allow to perform complex structural calculations as well as to provide access for the better visualization, estimation of cost and scheduling [14]. From the structural engineer's viewpoint, the philosophy of BIM influences the conceptual design, structural analysis and production of technical drawings. This will eradicate the errors in design and drafting, as well as minimize clash detections and reduce the overall cost associated with the structural design process. Furthermore, BIM systems offer a solution for improved scheduling, cost estimation, which consequently enhance the competitiveness of the design offices [14].

Designing of building and construction management are considered as the mature application stages of BIM in the AEC industry. The design of building process usually generates a large amount of information and data primarily in the architectural, structural and MEP design [15]. The structural design is quite a complex process and is mostly dependent on the information produced and shared from the architectural design. A structural model is considered as an important constituent of the BIM model and its role in the building design process is pivotal [15].

Due to the integration of BIM in structural design, most of the recent construction projects have implemented the ideas of BIM in the design phase of construction. BIM-based structural design has enhanced performance and productivity as well as decreased the cost during construction due to an organized modelling process and data exchange standardization. BIM can accelerate the communication and collaboration time by acting as the centre of design information, which will assist to handle large amount of data as well as to give the right information at the right time [16]. The applications and development of BIM-based engineering in the future will benefit structural engineering due to the software for the parametric drawings, economical computational power as well as 3D visualization tool [16]. H.L. Chi et-al [16] studied the future trends of BIM-based structural engineering, which show focus on the following five major areas.

- In the development of parametric structural design, the traditional geometrical parameters for the architectural modelling can be expanded to introduce further functionalities, factors related to safety and sustainability which can be broadly used in the structural design.
- Structural optimization needs to be considered and implemented at the conceptual design stage, which will help to provide more flexibility in the design as well as analysing various optimization solutions regarding the perspective of a various design approach.
- Tools which can be used to improve and support decision-making need to be developed dependent on BIM database as well as other relevant visualization technologies.
- Development of numerical methods with better computational power and showing high performance for solving multi-scale design and optimization problems.
- Extension and strengthening of collaborative works for BIM-based data exchange abilities, which will enhance the quality of structural solutions as well as minimize the redesign issues in the design stage.

2.2.1. Architectural design to structural analysis

In a construction project, the architectural design and structural analysis are considered as two distinct domains as they have different objectives in which the former defines configurations of various architectural components while the later analyze the mechanical and structural properties of the building [65]. The interoperability and data exchange between architectural design and structural analysis has been discussed with the aim to analyze BIM-based structural analysis considering data transfer between different software in the following ways [65].

1. Using native file for data transfer considered as a direct link.
2. Using application programming interface (API) for data transfer with a BIM platform and considered as a direct link.
3. Indirect transfer of data through third-party software focusing on industry foundation classes (IFC).

In the first case, the structural model is transferred from Revit to Robot using native file, while in the second case the data is transferred to CSI software including ETAB, SAP2000 and SAFE2016. The authors performed a case study in which they analyzed the BIM results from architectural design to be used in structural analysis using the above-mentioned data exchange paths. The authors modelled a simple concrete frame structure in Revit provided the information regarding the structure geometry, material properties and its type, load combinations as well as the boundary conditions. The results of the interoperability show that information was missed in all cases. However, more information was missed in the indirect data transfer as compared to the direct data exchange. The authors found that in the indirect data transfer using IFC, the values of material properties such as elastic modulus (E), shear modulus (G), Poisson’s ratio and thermal expansion coefficient were changed. However, only thermal expansion coefficient was changed during the direct way of data transfer. Furthermore, the authors observed that the self-load and section properties were missed in all cases while load and load combinations and footing information were missed through indirect data transfer using IFC between Revit and ETAB. The authors recommended that the developer of BIM software need to build complete IFC support in order to fully import and export required information within the BIM platform. It was recommended that the reason of information missing as well the value changes for some parameters need to be identified. This study was limited to only one structural model, so different type of structural models need to be investigated to have a better understanding of the interoperability issues [65].

2.2.2. Effects of BIM-based structural design

The BIM-based structural design needs to be gradually implemented as well as upgraded and improved eventually due to its large number of effective uses in the AEC industry. The impacts of BIM-enabled structural design ranges from providing the understanding of issues in structural designing, increasing the collaboration and interactive abilities among the design teams as well as throughout the design processes.

The objective of BIM is to consider the dynamic factors in addition to the static variables including material properties and geometrical limits, which affect the design performance throughout the construction process. The structural designer should look at the broader picture of the construction plan and needs to be familiar with the building functionality, sustainability concerns and safety besides the traditional structural criteria.

Different design teams including architects, engineers and planners require to have better coordination among each other to prevent the conflicts in the design and to solve critical issues because of the large number of design variables than the conventional structural design approach. Due to frequent and enormous cooperation among the design teams, information and communication loss may occur in the data exchange processes, which can cause critical issues to the BIM-based design approach [16]. To reduce the interfacing gaps, the data format needs to be standardized [17]. Structural designers have the flexibility to better analyse the results and to make structural adjustments using new visualization platform including 3D modelling tools that contain several characteristics of structural components [18].

2.2.3. BIM-based interoperability

For the development of BIM interoperability, levelling models are proposed which shows the contribution of the interoperability using BIM in the competitiveness of the companies. The five levels of interoperability are communication, coordination, cooperation, collaboration and channel as shown in Figure 1 [19].

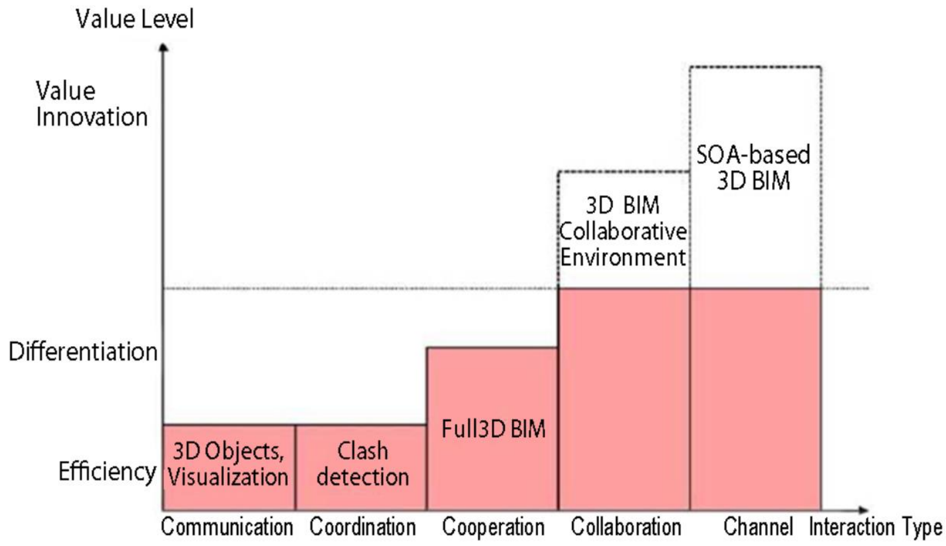


Figure 1 – Interoperability levels [19].

BuildingSmart has produced several document types to improve the interoperability within the BIM platforms. These documents include Information Delivery Manual (IDM), Model View Definitions (MVDs), International Framework for Dictionaries (IFD) and Industry Foundation Classes (IFC). IDM explains the type of information that is required to be provided through a defined way and at which phase in the project. MVDs establishes the information exchange processes and is associated with the requirements of software for the implementation of IFC. While IFD also known as BuildingSMART Data Dictionary (bSDD) is a library for dictionary of terms. IFC is an open standard for BIM which is used for the exchange of information between different platforms [20].

There is still a lack of enough support to exchange information between diverse software applications as well as the automation of structural analysis in an open environment [66]. One of the most important issues is the exchange of reinforcement bars in concrete structures. Most of the software doesn’t support to export reinforcement information as well as the IFC is not completely ready to receive such kind of information [67]. In addition to reinforcement bars, the loads are also not transferred. Some authors have suggested that reinforcement should be shared as individual elements within the assembly by taking into account its connection to the parts in which the reinforcement is provided to improve the interoperability of reinforcement bars [68].

A five-gap analysis study was performed in which the authors checked the interoperability between Revit and TQS software using IFC in the year 2011 and 2016. The authors exported the columns, beams and slabs considering its GUID (Globally Unique Identifier), placement, geometry and material. In this five year gap, the interoperability was improved by 38%, from 0.567 during the analysis in 2011 to 0.784 during the second analysis in 2016. Although there is a significant improvement observed in the exchange of information during the last few years, but great difficulty was found in processing objects with openings and curved geometry as well as mix up of permanent and variable loads [69].

The literature presents three scenarios for considering shapes of the modelled objects including objects which are disjointed, nested objects and overlapping objects. As the structural elements are usually overlapping, this approach is quite relevant for concrete structures which are cast-in-place. Furthermore, to reduce error in the quantity take-offs for concrete, the software needs to deduct the areas which are intersecting [69].

2.2.4. Visual programming for building information modelling

Visual programming is comparatively newly implemented in the AEC industry although it is quite developed in many other fields [21]. It is being used for the development of a detailed algorithm and to adjust the output in a parametric manner. The information can be easily utilized and understood by the user as it is expressed in the form of graphical symbols [22]. Some of the visual programming languages which are being used in the BIM environment are Dynamo, Grasshopper and Simulink etc. The user interfaces of the visual programming languages are different than the text-based programming languages such as Python, C#, Java etc, in which the code is typed in a text editor [21]. The selection of a programming method is based on the programming skills of the user, task complexity, its size, utilization frequency etc. Visual programming gives a prompt response by linking the data with the geometry. This can give a bi-directional link, which can be more supported in the earlier phases of the design. In the AEC industry, visual programming has been used in construction detailing [23], structural performance [24], fabrication [25] and landscape architecture [26] as well as in few others disciplines of building design and construction. Introducing visual programming in BIM processes is getting to increase and is becoming very popular in academia and industry. A brief introduction of a visual specific programming tool, named Dynamo is presented below (choice motivated by the fact that this was the tool chosen in the scope of this dissertation)

Dynamo is a visual programming tool/language and its first version was released in 2011. The power of the overlaying BIM Platform (Autodesk Revit) is extended with the use of Dynamo which provides access to Revit API in a comparatively simple way. Instead of code typing, Dynamo generates programs by manipulating graphic elements named as “nodes”. Each node is considered to do a particular task in Dynamo and has minimum one output and input which is then connected to other nodes using wires called connector as shown in Figure 2. One of the relevant advantages of Dynamo resides in its quick access/availability to a wide library of nodes with predefined functions that can reach significant complexity. Furthermore, to perform a specific task, there is no need to learn the exact code. In Dynamo, a certain node can be simply searched in the library. The Dynamo script can be run either automatically or manually. To get good results with fewer errors and facilitate debugging, it is normally recommended to run the script manually. Some of the benefits of Dynamo are listed below:

- Automation of repetitive tasks;
- Easy and quick access to building data;
- Exploration of multiple design alternatives;
- Testing and checking of performance;
- A systematic approach to thinking computationally.

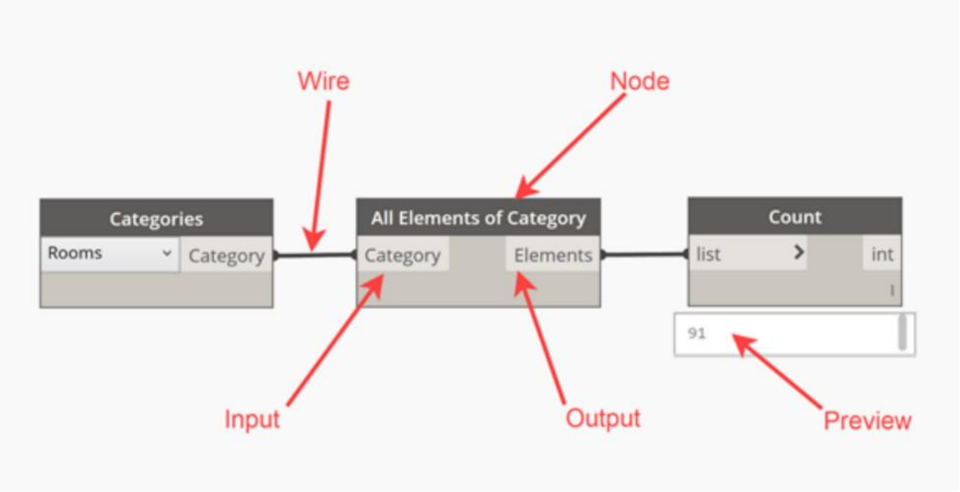


Figure 2 – Dynamo: example of nodes and their interconnection

2.3. Seismic analysis of existing buildings

Most of the existing buildings either collapsed or show severe damages till the end of the 20th century in earthquakes of moderate to large magnitude until the provisions for seismic design is being adopted. Both unreinforced masonry buildings and engineered structure show severe damages in both the developing and developed world, which led to the loss of hundreds of human lives during past earthquakes. Therefore, the seismic analysis and retrofitting of such structures against earthquakes are important due to a large part of Europe exist in the seismic zones.

2.3.1. Eurocode 8

Eurocode-8 referred as EN-1998 is the European Standard for the design of structures for earthquake resistance which focuses on the seismic design of structures. Similar to other parts of Eurocodes, EN-1998 also consider the limit state design method which is Ultimate Limit State (ULS) and Serviceability Limit State (SLS). ULS and SLS are a non-collapse requirement and a damage limitation requirement respectively. The structure is required to resist the ultimate design load without losing its integrity for the ultimate limit state requirements. While the structure must be serviceable when hit by an event that is more expected to occur. The recommended values for the probability of exceedance for ULS is 10% in 50 years (or return period of 475 years), while for SLS the probability of exceedance is 10% in 10 years (or return period of 95 years) [27].

EC-8 gives four different alternatives to do calculations concerning the procedure of analysis which is briefly described below.

a. Lateral static force method

This is a simplified method in which the effect of seismic forces is substituted by static forces that are distributed laterally on the structure. This method is valid only for buildings which are fulfilling the conditions of regularity.

b. Model response spectrum analysis:

This analysis method is using a linear elastic model and can be used for all kinds of buildings. In this method for each mode of vibration, the seismic actions are transformed into equivalent static forces or displacements. For each mode of vibration, the base shear, lateral force and acceleration is calculated and then combined by square root sum of squares (SRSS) or complete quadratic combination (CQC).

c. Non-linear static analysis

The non-linear static analysis procedure is also known as pushover analysis takes into both material and geometrical non-linearity. It is an incremental static analysis procedure used to determine the force-displacement relationship for a structure.

d. Time history analysis

Time history analysis is a non-linear dynamic analysis which is considered as the most accurate but time-consuming method. This analysis method is used to measure the seismic response of a structure due to dynamic loading of a representative earthquake. In this method, the seismic action is represented by one or more accelerograms that may not match entirely to future events.

2.3.2. Response Spectrum

EC-8 requires the following input data to obtain the response spectrum [27].

- **Identification of ground type**

The seven types of grounds are identified in EC8-1 and shown in Table 1, can be used as a basis for the impact of local ground conditions on the seismic action.

Table 1 – Ground types [27]

Ground Type	Description
A	Rock or other rock-like geological formation
B	Deposits of very dense sand, gravel, or very stiff clay
C	Deep deposits of dense or medium dense sand, gravel or stiff clay
D	Deposits of loose-to-medium cohesionless soil
E	A soil profile consisting of a surface alluvium layer, underlain by stiffer material
S1	Soft clays/silts with a high plasticity index (PI > 40) and high water content
S2	Deposits of liquefiable soils

- **Peak acceleration**

The peak acceleration a_{gR} is another parameter whose value can be taken from National Annex for different seismic hazard zones.

- **Importance factor**

Buildings are assigned different importance factors based on its consequences of failure for human life, socio-economic consequences of collapse as well as its importance for public safety in the immediate post-earthquake period. A higher value of importance factor is assigned for buildings with integrity during earthquakes is of vital importance and vice versa. The following four importance classes are described in EC8-1 as shown in Table 2.

This Building Importance Factor, γ_I is calculated for the desired return period T_L or probability of exceedance P_L.

Table 2 – Importance class of structures [27]

Importance class	γ_I	**Description**
I	0.8	Buildings of minor importance, e.g. agricultural buildings, etc.
II	1	Ordinary buildings, e.g. residential buildings
III	1.2	Buildings whose seismic resistance is of important e.g. schools, cultural institutions etc.
IV	1.4	Buildings of vital importance for civil protection, e.g. hospitals, fire stations, power plants, etc

- **Damping factor**

The factors which affect the amount of damping that the structure allow depends on materials and type of structures. The damping ratio can be determined based on the presence of plastic hinges, plastic behaviour of structural elements, the capacity of foundations and column to absorb energy as well as on soil-structure interaction. The damping ratio of $\xi = 5\%$ is being used in EC-8 if the advanced analysis is not possible.

- **Type of spectra**

The type of spectra is another classification which affects the shape of the response spectrum curve. Two types of response spectra are suggested by EC8-1. Type 1 is used if the magnitude of the expected earthquake (Ms) is greater than 5.5, otherwise, Type 2 is being used for regions with low seismicity (Ms ≤ 5.5).

- **Behaviour factor**

The value of behaviour factor q_0 for regular buildings in elevation for different structural types is given in Table 3.

Table 3 - Behaviour factor for different structures [27]

Type of concrete structure	DCM (Ductility Class Medium)	DCH (Ductility Class Higher)
Frame and Coupled wall system	$3.0*\alpha_u/\alpha_1$	$4.5*\alpha_u/\alpha_1$
Uncoupled wall system	3.0	$4.0*\alpha_u/\alpha_1$
Torsionally flexible system	2.0	3.0
Inverted pendulum system	1.5	2.0

Where α_1 and α_u are the values by which the horizontal seismic design action is multiplied in order to first reach the flexural resistance in any member in the structure and to form plastic hinges in a number of sections sufficient for the development of overall structural instability respectively while all other design actions remain constant.

2.3.3. Previous studies on non-linear static analysis

The research in the non-linear analysis procedures developed rapidly during the last few decades. Some of the literature related to nonlinear static analysis are presented below in the following paragraphs.

In 1974, Gülkan and Sözen indicated for the first time the significance of maximum displacement estimation as a response to an intense seismic motion that provides a base to the concept of nonlinear static analysis. They concluded on the basis of an experimental investigation on a one bay single-storey frame that the RC structures response is influenced by a decrease in stiffness and rise in energy dissipation capacity. The structure stiffness decreases, and energy dissipation capacity enhances when the displacement demand values are higher. However, linear response analysis having reduced stiffness and substitute damping of the SDOF system can be used for the approximation of maximum dynamic response. In accordance with the test results, they established a relation between the ductility and substitute damping. The main aim was to estimate the corresponding base shear to the maximum displacement as well as get to the maximum displacement limit provided the structure with sufficient strength [28].

In 1975, Freeman et al. developed Capacity Spectrum Method (CSM) to be used for the calculation of maximum displacement demand of SDOF system on the basis of "equivalent linearization method" [29].

Saiidi and Sözen in 1981 proposed the "Q-Model", for the determination of force deformation relationship of SDOF system when it was believed that nonlinear analysis should be used for determination of nonlinear analysis. Moreover, MDOF system was proposed to be represented as SDOF system for a structure subjected to ground motions for modelling the stiffness changes [30]. Other researchers including Saiidi and Hudson in 1982 and Mohele in 1984 modified the model and apply it for analysis of vertically irregular buildings.

N2 Method was introduced as a development of Q-Model by Fajfar and Fischinger in 1987 for buildings which oscillate primarily in a single mode. The N2 method is an aggregate of non-linear static analysis of MDOF system under a monotonically increasing horizontal load and non-linear response history analysis obtained from the nonlinear static analysis for a SDOF representation of the system. For the SDOF system, the maximum displacement demand of ground motion is calculated which is then used for the computation of maximum roof displacement demand of the MDOF system [31]. In 1996, Fajfar and Gaspersic used a force distribution which is proportional to the product of an assumed displacement shape and mass matrix [32]. FEMA 273, FEMA 356 and ATC 40 used the concept of non-linear static analysis as well as SDOF representation of the N2 method with changes in horizontal load force vector.

Some drawbacks in the CSM has been pointed out by Chopra and Goel in 2000 that the procedure may not converge or can give an impractical estimate of displacement under an unfavourable set of conditions. They concluded that due to the overestimation of equivalent damping, the CSM usually underestimate the displacement demand when compared to NRHA results [33].

In 1998, Krawinkler, H., and Seneviratna explained the relevancy of non-linear static analysis as a tool for seismic performance evaluation. Furthermore, the deficiencies of non-linear static analysis were pointed including lateral load pattern, the effect of higher modes as well as the ability to recognize all possible structural mechanism in addition to its adequate features [34].

To overcome the shortcomings of non-linear static analysis, adaptive procedures were adopted in the current researches. Paret et al. (1996) suggested the concept of performing various pushover analysis with force distributions that are proportional to the product of elastic mode shapes and mass matrix. In order to analyze the vibration mode which can lead to failure of the structure, a Model Criticality Index (MCI) was proposed [35]. Sasaki et al. (1998) extended MCI and proposed the Multi-Mode Pushover (MMP) method that deals with higher mode effects [36].

Chopra et al. (2004), proposed MMPA by combining the elastic contribution of higher modes with the inelastic response from first mode pushover analysis. In this procedure, pushover analysis is not required for higher modes of vibration as its effect is considered as linearly elastic, which simplifies and reduce the required computational effort [37]. Kalkan and Kunnath (2006) proposed a different pushover analysis method that utilizes an energy-based scheme and is derived through adaptive modal combinations (AMC). This procedure by using constant ductility inelastic spectra waive the requirement to pre-estimate the target displacement [38].

2.3.4. N2 pushover analysis

The N2 method is a comprehensive, relatively simple and non-linear procedure for the seismic analysis of reinforced concrete buildings. N2 method which is developed at the University of Ljubljana is based on the following steps [39]:

- Computation of lateral force pattern and structural data;
- Performing the nonlinear static analysis i.e. pushover analysis of multi-degree of freedom model (MDOF);
- Computation of a bilinear force-displacement relationship for an equivalent SDOF model;
- Determination of seismic demand for the SDOF system;
- Computation of seismic demand for MDOF model by transforming the displacement of SDOF model to the top displacement of MDOF model;
- Computation of damage analysis and evaluation of performance.

2.3.5. Pushover analysis

Pushover analysis is a non-linear static analysis under constant gravity loads and monotonically increasing lateral loads. Pushover analysis is a series of incremental static analysis performed to develop a capacity curve for the building. This procedure requires performing nonlinear static analysis of the structure that allows the monitoring of the gradual yielding of the structure component [41]. The building is subjected to a lateral load and the load magnitude increases until the building reaches the targeted displacement. This target displacement is determined to illustrate the top displacement once the building is subjected to design level ground excitation. Pushover analysis is used to produce a pushover curve or capacity curve that shows the relationship between the base shear (V) and roof displacement (Δ). The Pushover curve depends on structure strength and its deformation capacities as well as describing the structure behaviour after its elastic limit [42]. The pushover procedure consists of two parts. First, a target displacement for the building is established. The target displacement is an estimation of the top displacement of the building when exposed to the design earthquake excitation. Then a pushover analysis is carried out on the building until the top displacement of the building equals to the target displacement and the second one force-controlled type in which the total amount of force acting is estimated and applied to the structure and the analysis is carried out [43].

Some researchers identified the pushover analysis is an effective tool to present structure response which either cannot be visualized by elastic or dynamic analysis. It also illustrates design weaknesses that might remain hidden in an elastic analysis [44]. Some limitations of this method which decrease the accuracy of the result include a torsional effect in buildings, target displacement estimation, choice of lateral load patterns as well as recognition of failure mechanisms due to higher modes of vibration.

Eurocode 8 defines pushover analysis is a non-linear static analysis carried out under constant gravity loads and monotonically increasing horizontal loads. It may be applied to verify the structural performance of newly designed and of existing buildings for the following purposes:

- to verify or revise the overstrength ratio values α_u/α_1.
- to estimate the expected plastic mechanisms and damage distribution.

- to assess the structural performance of existing or retrofitted buildings for the purposes of EN 1998-3.
- as an alternative to the design based on linear-elastic analysis which uses the behaviour factor q. In that case, the target displacement should be used as the basis of the design.

➢ Buildings not conforming to the regularity criteria shall be analyzed using a spatial model.

➢ Two independent analyses with lateral loads applied in one direction only may be performed.

➢ For buildings conforming to the regularity criteria, the analysis may be performed using two planar models, one for each main horizontal direction.

➢ For low-rise masonry buildings, in which structural wall behaviour is dominated by shear, each storey may be analyzed independently. This requirement is deemed to be satisfied if the number of storeys is 3 or less and if the average aspect (height to width) ratio of structural walls is less than 1,0.

2.4. Previous studies on BIM-based Seismic analysis

BIM which in building industry shows the application of a new generation of information technology (IT) was restricted to drawings preparation in the past using computer-aided design (CAD). BIM-based 3-D visualization of building includes meaningful information of all building elements such as geometry, properties of materials, etc. [45]. The traditional and conventional process in the AEC industry for integrating various sectors were costly, time-consuming as well as the results had significant errors, and there was inconsistency in drawings due to lack of interoperability [11]. Many software tools are available these days for seismic analysis of structures but these software have no mechanism to share information with BIM tools [13]. So, there is a need to improve the interoperability between BIM tools and seismic analysis software for better non-linear analysis of existing structures.

Seismic analysis of structure generally requires the following main procedures.

➢ Development of a geometric model

➢ Discretization

➢ Pre-processing

➢ Analysis and post-processing

In the first step, the most usual way is the bottom-up approach in which a 3-D geometrical model is created initiating from primary elements. In accordance with the given schematic, each element is created in a successive manner following one after another. It has been observed that the creation of the analysis-suitable geometry needs approximately 57% of the total analysis time [46]. Due to this reason, Building Information Modelling (BIM) can act as an effective solution, which in engineering structure design considered as the second technological revolution [47].

In the last few years, Building Information Models (BIM) has gained a great interest in the AEC sector because of its several benefits as well as savings of resources throughout the design, planning, construction and operational phases of buildings. Currently, the construction sector largely focuses on activities such as analysis and renovation of buildings and retrofit interventions of existing buildings in countries where the construction of new buildings is low [48].

BIM provides an opportunity to be fully integrated with FEA (finite element analysis), thus allowing to perform monitoring of structural design throughout the lifecycle of the structure. Fedorik et al. [49] show the experiences of large buildings and bridge projects regarding the interoperability of FEA and BIM. The authors further presented the potential model of BIM-based FEA which shows some important findings. Due to interoperability issues, engineers mostly perform FEA separately than the BIM platform, which reduces the efficiency of the design.

There are some software applications which are performing interoperability by exporting only the geometry in .DXF or .DWG format, which may cause information loss depending on the complexity of the geometry. These methods are usually unable to export the boundary conditions and material properties to the FEA software. Therefore, there is a great significance of complete interoperability between BIM and FEA in which the digital data from the BIM model will be transfer to FEA taking into account all required parts required for the analysis. This BIM-based FEA approach is illustrated in Figure 3 [49].

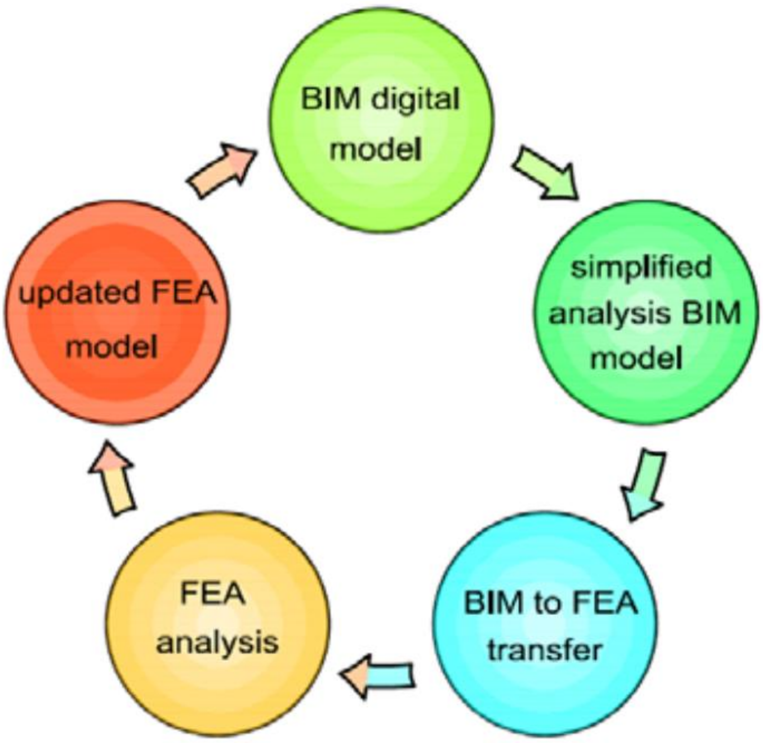


Figure 3 – BIM-based FEA approach [49]

The research from the last decade show more tendency towards BIM-based damage estimation due to seismic loadings [50], assessment of seismic performance [51], seismic risk mitigation [11], BIM-based sustainability [52, 53] seismic retrofitting strategies using BIM-based approach [3,13]. The previous studies involving BIM-based seismic analysis is presented in the following sections.

2.4.1. BIM-based framework for sustainability, damage estimation and visualization of seismic cost

The construction industry generates a huge amount of waste as well as uses a large fraction of natural resources and energy which ultimately cause an adverse effect on the environment. It has been studied, that almost 40% of the total energy use and 36% of the emission of the CO_2 is based on the construction industry in Europe [54, 55]. Several researchers have studied LCC (life cycle costing) and LCA (life cycle assessment), which are used to measure the economic and environmental impacts of a project respectively throughout its life cycle [8, 54,52]. The traditional procedures for the assessment of economic losses are quite unpopular due to its complex nature. Alternatively, a BIM model having the information level appropriately defined can be used for LCA and asset management.

Literature shows several ways to integrate BIM with LCC and LCA. The first approach uses different tools to perform LCC and LCA analysis. In the second approach, the overall environmental impacts of a project are determined by connecting quantity-takeoff obtained from the BIM model to LCA database [53, 56, 57]. While the third connect and provide LCA information to BIM which is considered as the first move to environmental integration [53,57]. The third approach is more suitable and can be used for the refurbishment of the infrastructure if the information regarding LCC/LCA is already provided in the BIM model. In this case, new elements will be added to the BIM model followed by running the new analysis [53].

In one of the research studies [53], the authors analyzed the capacity of integration of information with the BIM models to minimize the issues related to interoperability and hence enhances the capability of such analysis. Moreover, to analyze the exchange and processes of information required for the analysis of LCC and LCA, the IDM and MVD procedures were resorted. Finally, the authors developed a framework for the analysis of BIM-based LCA and LCC, and further verified the compatibility of current IFC schema for the proposed IDM and MVD methodologies [53]. It was noticed that automatic streamlined analysis of LCC and LCA can be performed by including economic and environmental information in the BIM model by the manufacturers.

In the other research studies [52], the authors analyzed and compared the economic and environmental effect linked with strengthening and dismantling of precast structural members of an existing building with the construction and dismantling of the precast structural member of a new building having the same properties using BIM-based LCA. The authors concluded based on the analysis of LCA and LCC that the refurbishment of the existing building is more advantageous in terms of the associated costs and the reduction of CO_2 emission than the construction of a new building. Moreover, the retrofitting of the building retrieve the functional performance of the building, as well as the safety and durability of the structural members, are ensured.

In the research performed by Mehdi et al. [50], the environmental impacts and the cost of damages of a damaged building under seismic loading are assessed by developing a semi-automated method. The main aim of this study was to perform and integrate BIM-based LCA, LCC and retrofitting of a building by developing a comprehensive approach. This integrated approach will facilitate the exchange of data and information between different teams which will increase the quality and efficiency of the project by performing the modelling procedure only once.

In 2018, a BIM-based decision-making tool was developed to determine different alternatives for post-disaster reconstruction [58]. This tool will quickly and automatically estimate the construction cost of the proposed alternatives in post-disaster situations. The authors concluded that utilizing BIM-enabled cost estimation tool will help to precisely calculate the overall cost of the project and will assist in the decision making to choose the most appropriate choice for reconstruction in a short time. Furthermore, the authors revealed that this application will eliminate the mistakes in quantity takeoff and thus will save money by evaluating different alternatives. This application code can only be used for buildings which are completely devastated. For partially damaged structure, this code can be advanced to determine the cost associated with reconstruction for partially damaged structures [58].

A BIM integrated approach based on Assembly-Based Vulnerability (ABV) methods is proposed by Christodoulou et al., [59]for estimating the damage analysis and quantification of cost for retrofitting of a building after a seismic event. This integrated BIM-based approach is used to measure the seismic vulnerability and structural performance using seismic analysis procedures. The procedure utilized accounts for building elements along with their fragility curves and then implement a BIM-based approach to automatically estimate the damage, cost and visualize the corresponding retrofitting work.

In this integrated procedure, a BIM model of the case-study building that contains both structural and non-structural components is constructed. In addition to the BIM model, a relational database management system is simultaneously made which includes the Work Breakdown Structure (WBS) of the project having the basic building components, Construction Specifications Institute (CSI) code and the unit cost. The BIM model is further used in the building's structural analysis as well as to seismic loads by using the fragility curves. The damage occurs to each building component is measured based on the fragility curves related to each component after performing the structural assessment. For the measurement of damages and its state after performing the structural analysis and fragility curves associated with each building components is used as a descriptor for damages which can be visualized by adequately colouring in the BIM model. The damage measure is either shown as a continuous variable or discrete variable. For a continuous variable, the damage measure is in the range of [0, 1]. In the case of discrete variables, the damage is indicated by green, yellow, red or black colour, which shows the different severity of the damages. Continuous variables are used to represent schedules and cost and are coloured on the contour plot. This approach supports to perform and automate the structural analysis, cost as well as the scheduling and then integrate it with BIM for the comprehensive assessments of damages after a seismic event [59].

2.4.2. BIM-based seismic risk assessment

Earthquakes have severe consequences on the built environment. Various uncertainties need to be defined for measuring the seismic risk associated with a building. Some researchers tried to use BIM technologies to study the assessment of the seismic vulnerability of existing buildings. BIM-based seismic analysis can give important information on structural details and reduces uncertainties which lead to improving the analysis results [11]. BIM can readily provide reinforcement information for concrete buildings, details of connection in case of steel structure [11, 60] accurately measuring the seismic mass [11, 61] and can do real-time export from BIM tool structural analysis software to execute seismic analysis [62].

The feasibility of performing a detailed seismic assessment depends on the capacity of BIM to arrange and export information to external software. A particular software will be used to process information of structural members, utility system and architectural units etc. to instantly provide data for experts of a particular department as shown in Figure 4 [11]. Moreover, the multi-disciplinary data which is needed for seismic assessment will be accessed accurately by developing a specific risk assessment program which should be accordant with the program running outside the BIM platform. This will enhance reliability as well as decrease the uncertainty and permit to perform quick and efficient analysis [11].

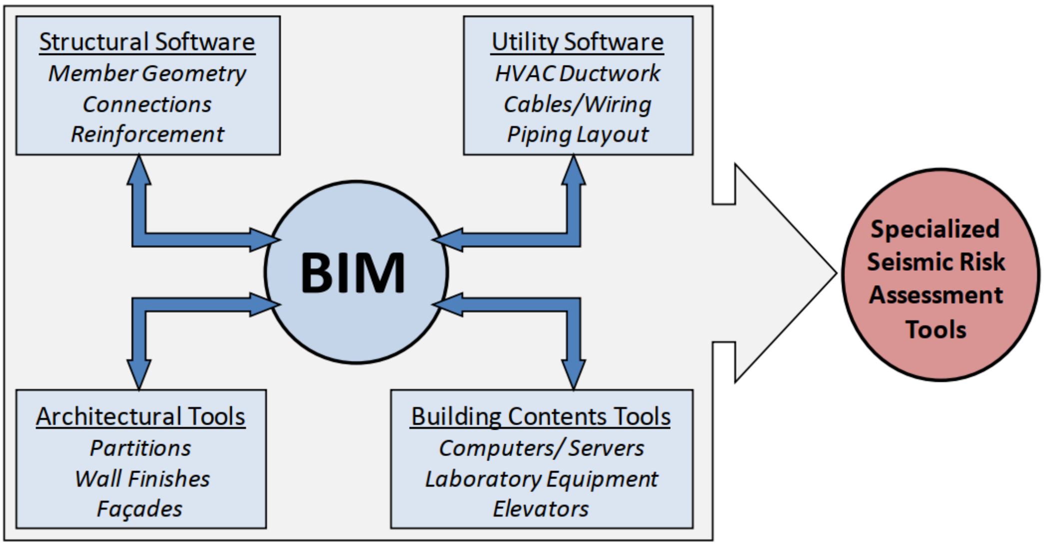


Figure 4 – BIM as a master building repository [11]

The data required for post-earthquake assessment of structures can be obtained by combining structural monitoring technologies with BIM technology which will have the significance to provide the structural data readily and will lead to quickly perform the post-earthquake inspection. Some of the significances of BIM-based structural monitoring are stated below [11].

- Timely information is provided to the owner stating if the building has likely to be damaged or not.
- Decreases the requirement of experts to examine an affected area.
- It allows to readily assess the effects of aftershocks which minimizes the number of inspections needed and hence decreases the risk for inspectors.

In the research performed by Carmen et al. [51], the BIM processes have been integrated to perform the analysis of the seismic vulnerability of educational buildings that have been constructed at the end of 20th century, to improve the quality of information required and perform the numerical simulations as well as to quantify the damage and repair costs due to an ultimate earthquake.

The authors concluded that it is possible to define a BIM model which contains all the structural and non-structural components of the building, as well as the information regarding the location, fragility characteristics and the cost of each element is saved in a single BIM model [51].

In another research, a methodology was proposed and implemented as shown in Figure 5 which include in informative modelling for analysis of seismic vulnerability. In the research, the data is collected for the existing buildings using non-destructive testings and then the structural data is integrated with the BIM model. Furthermore, a finite element model is prepared by implementing either the existing BIM LOD or an improved level of details which shows the recent state of knowledge is explored as well [63].

The authors presented some of the guidelines to draw a BIM model that can be effectively used for dynamic analysis. The authors found that the lack of defining material for structural elements, inaccurate definition of beams and columns as well as lack of defining the boundary conditions are some of the key shortcomings when analyzing existing BIM. To improve the export from Revit model to the structural model in the context of usefulness for the vulnerability analysis, the following guidelines were suggested [63]:

- Defining material for all type of structural elements;
- The accurate geometry defined for all structural elements;
- The connections and constraints in different elements of the structure to fulfil the consistency and compatibility criteria;
- Distribution of different structural loads on the structural elements.

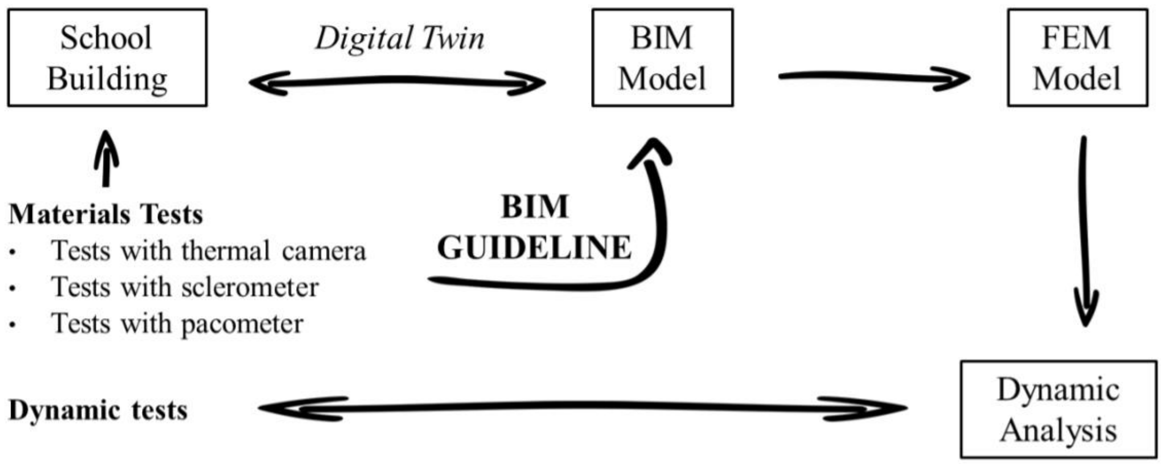


Figure 5 - Framework for proposed methodology [63].

In one of the studies, a prediction method is proposed which is based on BIM and FEMA P-58 to assess the seismic loss which is important for the structure resilience [64]. In this procedure, a BIM-based algorithm is modelled to foresee the damages of the component using time history analysis as well as fragility curves. The main steps for the BIM-based FEMA-P58 seismic loss prediction procedure include the prediction of damages and losses as well as visualization of the results. The framework for this procedure is shown in Figure 6 [64].

In the first step, the mapping relationship is established from the BIM components to the Performance Groups (PGs) in FEMA P-58, for predicting the damages. Afterwards, BIM-based time history analysis is carried out to get the engineering demand parameters, avoiding the manual modelling of the structural model. Furthermore, the fragility curves in FEMA P-58 are incorporated for the calculation of damages to performance groups. The damage state of the components is obtained by mapping back the damage of performance groups to the structural elements in BIM [64].

In the second step, the seismic loss of each component is predicted by creating an ontology-based model which will accurately measure the components data taking into account the deduction rules that uses BIM and a database for the unit repair cost. The losses to the whole structure are calculated from the unit repair costs for damage states of the components. In the last step, the visualization is displayed to observe the component damage and loss using BIM technology in a virtual walkthrough [64].

The authors concluded that the integration of BIM with FEMA P-58 will avoid manual structural modelling for time history analysis after using the above mentioned BIM and FEMA P-58 framework on a pilot six-storey building.

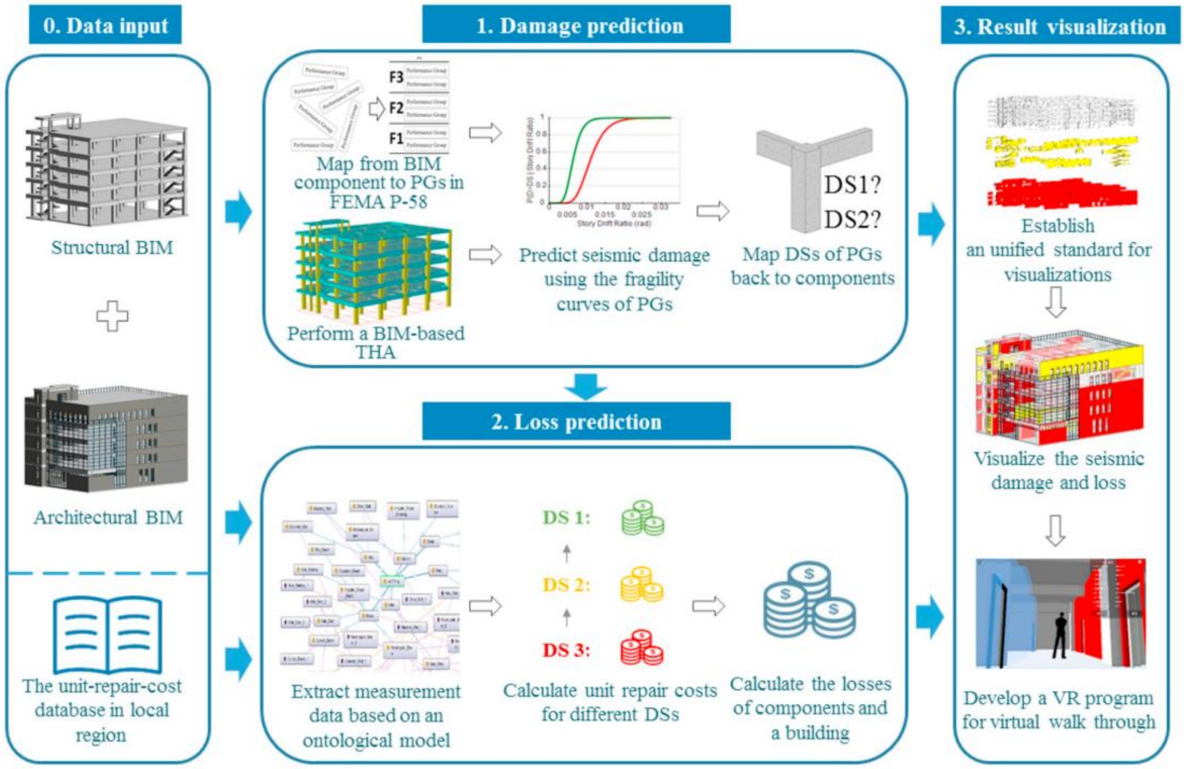


Figure 6 - Framework for damage, loss prediction algorithm [64].

2.5. Summary:

This chapter explains the seismic assessment using EC8-3, pushover analysis, BIM-based structural design, sustainability, life cycle cost analysis, and damage analysis among others. Although the application of BIM has been found to be quite wide, but it is not yet fully utilized in the context of BIM-based seismic assessment especially the current literature doesn't provide enough information regarding the establishment of a BIM-based framework for performing seismic analysis. It was found that there is still a gap between BIM-based seismic assessment considering the interoperability of the geometry as well as the material properties, reinforcement data, and especially infill walls.

3. PROPOSAL OF A FRAMEWORK FOR BIM-BASED SEISMIC ANALYSIS

3.1. Introduction

This chapter presents the proposal of a framework for interoperability that can support structural engineers in the scope of verification of seismic safety, with pushover analysis, of existing buildings in specialized software for the purpose (SeismoStruct), which was not yet set for BIM-framework interoperability. The challenge was to build an interoperability framework based on the modelling platform (Autodesk Revit 2020), that suited in the best way the task of data introduced into the BIM authoring tool, whereas allowing the innovative consideration of infill walls in the seismic analysis. Apart from the general presentation of the framework, and the intricacies of its implementation and operation, this chapter also shows the results of the application of the framework to the seismic assessment a pilot application (RC building) using pushover analysis. Particular attention is given to the capacity to consider explicitly the effects of infill walls.

3.2. The overall framework

3.2.1. Performance requirements

A set of performance requirements were directly set at the beginning of the developments, as to keep efforts of development/implementation well focused. The following performance requirements and capabilities are considered:

- To fully export the necessary data from the BIM modelling platform to the seismic pushover analysis software, which include all relevant data, such as the geometry of columns, beams, infill walls, material properties and supports.
- To limit the operation of the structural engineer on the seismic analysis software to the verification of the input data and to provide basic details like the number of steps, target displacement etc. and then launching the calculation and perform the critical analysis.
- The modelling rules/definitions for the framework/script to operate should not have any kind of conflict with the other BIM uses intended from the structural BIM model (e.g. automatic drawing generation, quantity take-off, interoperability with general-purpose structural analysis software).

3.2.2. Assumptions

A set of assumptions is defined, which can assist in understanding the reasoning behind several of the choices and simplifications are taken throughout the description/development of the framework/workflow:

- The framework is devised to be applicable in existing buildings, but there are no actual limitations on applying it to new construction.

- Slabs are considered as rigid diaphragms and there is no need to model slab in Revit if the purpose of the modelling is just to perform the seismic assessment.
- Reinforcement is not explicitly modelled in the structural elements but rather placed as non-graphic information in each relevant element on the BIM modelling platform.

3.2.3. Software

Autodesk Revit 2020 and SeismoStruct were used for the development of the BIM model and seismic assessment of the existing structure respectively. Autodesk Revit was used because of its availability at Newton as well as its wide penetration on the global market, making this work representative to a very large number of structural engineers. Moreover, the capability of customization and extensions with Dynamo scripting language and even further API programming, if necessary, make this tool a preferable choice. Regarding the selection of SeismoStruct for the seismic assessment of existing buildings, the main reasons were related to its high specialization for the task and its cost-effectiveness tool design offices that already own licenses for general-purpose software and only require specialized software for the pushover analysis.

3.2.4. Workflow

In this dissertation work, it is attempted to assess the seismic performance of an existing building by using a BIM-based framework. The explanation of the workflow of the framework is based on the diagram of Figure 7, which contain labels for each activity/part, from 1A to 7A. First of all, based on the availability of all the necessary data for the job (Figure 8-1A), the building is modelled in the selected BIM authoring platform (Revit – Figure -2A), following the modelling guidelines stated in section 3.4.1. Because of the fact that SeismoStruct is not able to import IFC data, specific developments were needed for the interoperability of data. This was achieved through the implementation of a Dynamo script, which can be run by the user in the GUI of Revit, according to step 3A of Figure 7 (using Dynamo player). After the script is successfully executed, a text XML file will have been generated, in an apt state to be directly inputted into SeismoStruct, and then to perform a non-linear static analysis to evaluate structural response for earthquake loading conditions (stages 6A of Figure 7). By analyzing the post-processing results including the base shear-displacement relationship, drift ratios, and development of plastic hinges etc. for different loading conditions, the results will be interpreted and evaluated. Of course, upon any decision of strengthening or change in the modelling parameters (e.g. for a sensitivity analysis on critical parameters), the whole process can be repeated conveniently with basis on the BIM model available from stage 2A of Figure 7.

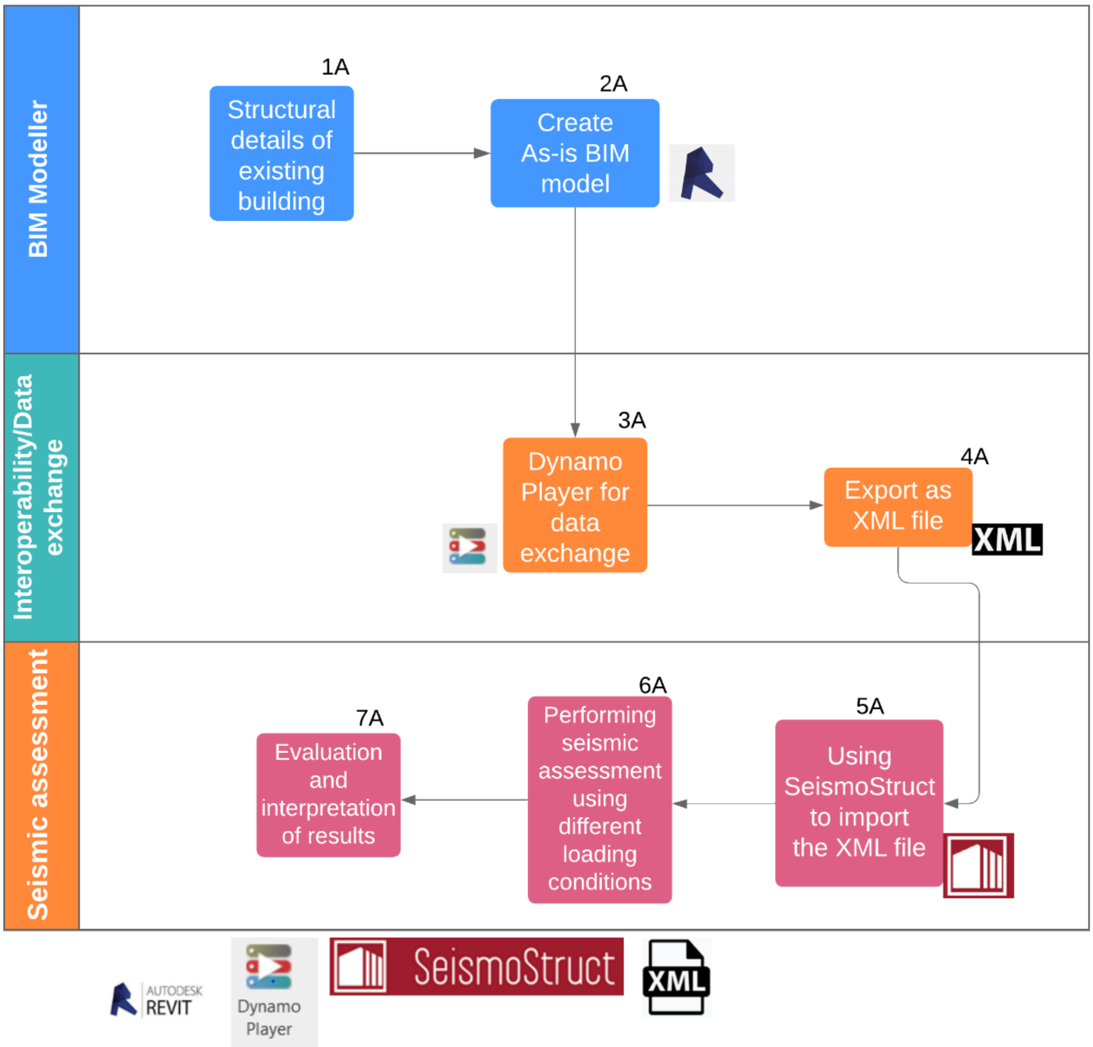


Figure 7 – Workflow for the proposed methodology

3.3. Implementation of interoperability script

The Dynamo script is developed to ensure the interoperability between Autodesk Revit and SeismoStruct. The script has been developed for application in RC building containing columns, beams and infill walls. Further applications to include shear walls, steel structural elements, or any other addition can be considered with relative ease to widen the applicability of the script/framework.

3.3.1. Description of data requirement

For the successful interoperability between Autodesk Revit and SeismoStruct using this script, it is required to provide the following non-graphical information to the elements in Revit.

- For structural columns and beams, the information related to concrete cover, width and depth need to be provided as the Type parameter to all elements. Furthermore, the compressive strength of concrete and yield strength of reinforcement needs to be attached to all structural elements.

- The reinforcement information for these structural elements needs to be provided in the form of non-graphical information.
- In case of infill wall, the thickness of the wall, compressive strength, tensile strength, Young's modulus, shear bond strength and maximum shear resistance need to be provided as a Type parameter.

3.3.2. Modelling requirements

The script was developed for direct use of the geometry/elements of the BIM model, while not operating at the level of the 'analytical model'. There were two main reasons for this: (i) Newton is already using the 'analytical model' for interoperability between Revit and Autodesk Robot, hence having different requirements and modelling strategies for such interoperability; (ii) the geometrical corrections needed for the framework proposed herein are relatively simple to program, hence not requiring the artefact of an 'analytical model' to support modelling simplifications/adaptations.

For the modelling of structure in Revit, the following guidelines need to be followed to successfully use the framework for exporting the structural model to SeismoStruct using the Dynamo Script.

1. The model needs to have two structural categories i.e. columns and beams. To additionally study the effect of infill walls on the seismic capacity, the 'wall' category can be included in the model as well. In Revit, categories are organized into families of elements with similar purposes and characteristics such as column is a category which can be subdivided into families including round columns and rectangular columns. Revit category can't be deleted and each element in Revit belongs to a specific category.
2. For the modelling of columns and beams, first, the columns are modelled to the required level and then beams are modelled up to the columns. This is a common procedure to model a frame structure as hence offer no issue with other BIM uses.
3. The dimensions which include concrete cover, depth, width of both beams and columns and material properties need to be provided as type-parameter to these elements as shown in Figure 8. The material properties include the strength of concrete and yield strength of steel to be specified for these elements. These parameters need to be provided only once for each element and shouldn't be duplicated, which will create difficulty for the script to choose the right parameter. In Figure 8, where Offset Base and Offset Top can be seen, these information is not useful for the export and can simply be disregarded. The parameters such as Offset Base and Offset Top are by default parameters defined in Revit and therefore has no significance in the export process presented in this dissertation.

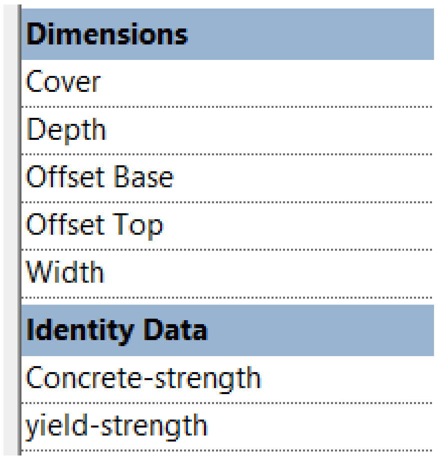


Figure 8 – Identification of properties as type-parameter

4. The reinforcement information needs to be attached to structural elements as type-parameter in the format shown in Figure 9. The reinforcement data shown in Figure 9 is explained with the help of Figure 10. For shear reinforcement, the number of shear legs are considered in each direction and is marked as stirrup-width and stirrup-height in the figures below. For column reinforcement where lower and upper bars don't exist, the concept can be understood in reference to global X and Y axis which can be drawn at the centre of the column. The upper and lower reinforcement will be considered as to whether the reinforcement is above the global X or not. If the reinforcement is above the Global X-axis, it will be considered as an upper bar and vice versa.

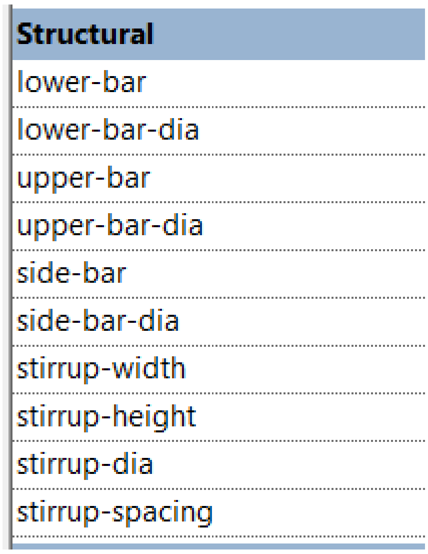


Figure 9 – Reinforcement information for columns and beams

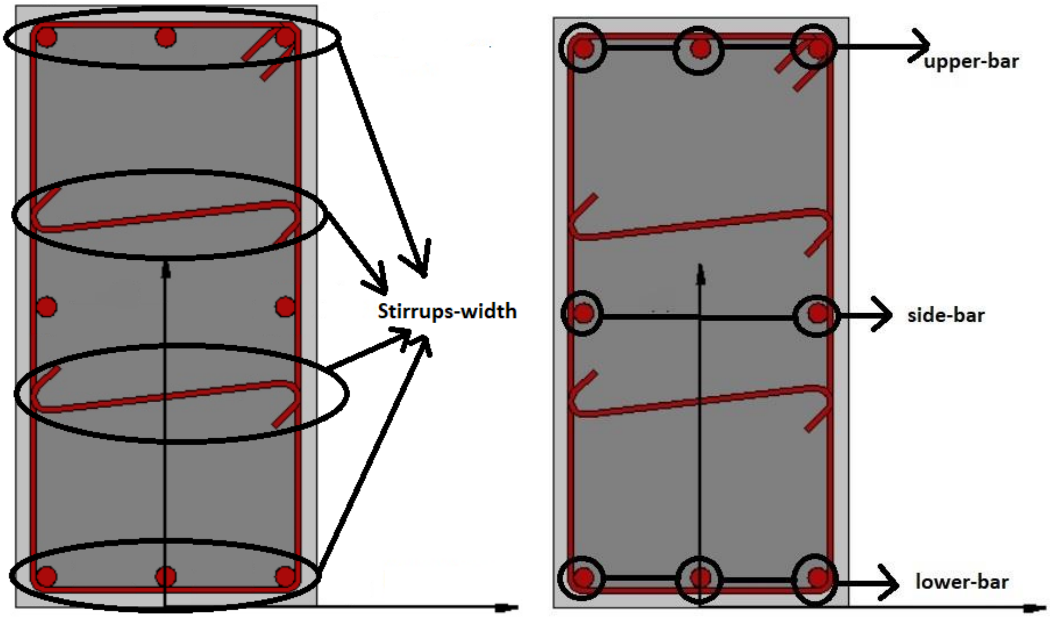


Figure 10 – Explanation of nomenclature used for the reinforcement data

5. The following units are required to be used for the above parameters.
   In case of cover, depth and width of the beams/columns, the unit need to be used is meter (m), while strength should be provided in kPa. The size of both longitudinal and transverse reinforcement should be provided in millimetres (mm), while its spacing is provided in meter.
6. The type-parameters which need to be provided in case of defining the infill walls are shown in Figure 11.

Structural
wall-thickness
compressive-strength
specific-weight
tensile-strength
young-modulus
shear-bond-strength
max-shear-resistance

Figure 11 – Infill wall parameters

7. For exporting foundation of the structural columns to SeismoStruct, an isolated footing needs to be provided to all columns in Revit. The script will detect the footing and will export it to SeismoStruct as fixed support (the stiffness of the support and even possibility of uplift may be considered in further versions of the script but are not possible to define in the current version of the script).

3.3.3. Interoperability format for data – XML

In this section, the structure of XML format which is exported by using the developed script is explained, showing how the data is structured. Furthermore, it shows the number of sections that are contained in the XML file.

The XML format starts with the program which is common data for any type of seismic analysis using SeismoStruct as shown in Figure 12.

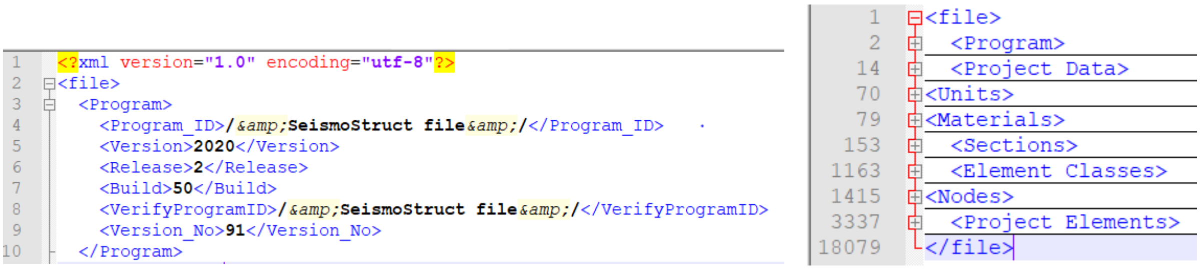


Figure 12 – XML program data (left), overview of the exported XML (right)

The next is the Project Data which contains information regarding the type of seismic analysis, number of nodes and number of elements etc. are presented. The project data is followed by the units used in the project and then all the materials are defined. The list of units included in the XML file is length, force, mass, acceleration, stress and weight. The developed script assumes to take the SI (Standard International) units for the measurements of the above quantities. After that, sections are defined for all structural elements which include the materials assigned to these members, section dimensions, as well as the reinforcement information and its pattern, is presented. The sections are followed by element classes which explained the type of plastic hinges applied to the structural elements is defined. In this case, the generated script presumes to have Inelastic plastic-hinge force-based frame element – infrmFBPH at the member ends with a plastic hinge length of 16.67% which is the default value for the plastic hinge length defined in SeismoStruct. When the sections and elements classes are defined for all structural elements and non-structural infill walls, nodes are defined, which provide the coordinates of all column ends. These nodes are connected further in the project elements where element classes are assigned to them. The above interpretation of XML file can be explained using Figure 13.

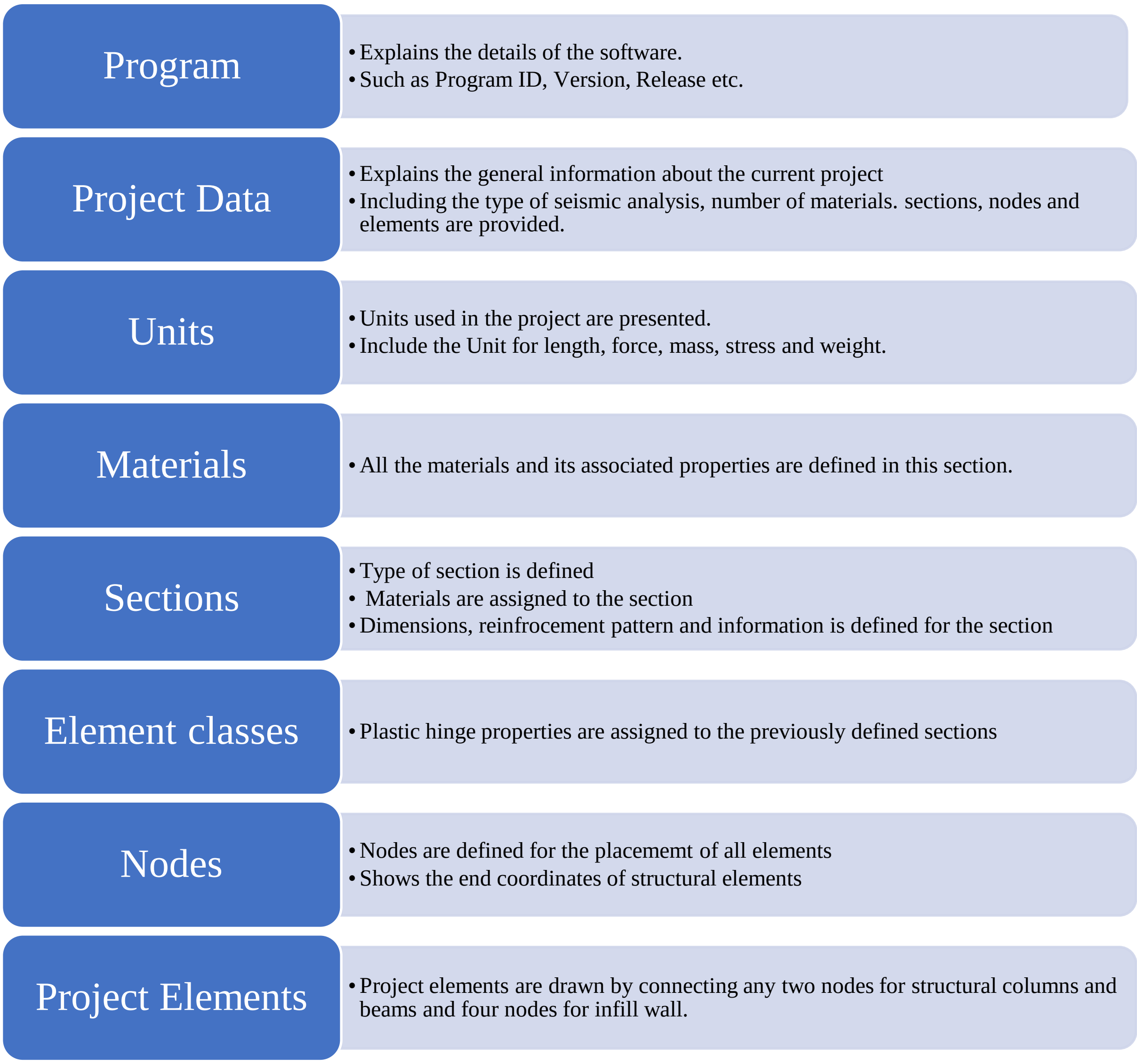


Figure 13 – Main details about the XML format for SeismoStruct

3.3.4. Dynamo script

To export the BIM model to SeismoStruct, a framework was built-up in Dynamo to develop interoperability between Revit and SeismoStruct. This framework will export the geometry, material properties, reinforcement data as well as foundation details for all the elements defined in Autodesk Revit. Due to the complexity and large size, it's not possible to show the whole script on a single page. Therefore, the detailed structure of the Dynamo script is broken down into parts which are presented in Appendix I. The framework in Dynamo consists of the following main parts.

1. Defining input category for structural members and non-structural infill walls;
2. Retrieval of input category and type name;
3. Extraction of metadata of structural members;
4. Extraction of node coordinates from the Revit Model;
5. Checker for spaces;

6. Defining sections and element classes;
7. Defining project elements;
8. Integration of the whole framework;
9. Defining a file path for exporting to XML file.

The working principle and a brief explanation of the above list are presented below.

1. Defining Input category

The input categories which include both columns and structural framing are defined. It takes the type properties which are already defined in Revit for these structural elements as shown in Figure 1-1 of Appendix I. The input category for structural framing takes the width, height and concrete cover of the beams while the input category for columns takes the width, depth and cover. The category for the infill wall is also added to the script to study the effect of infill walls in the seismic assessment.

2. Retrieval of input category and type name

All the elements of the input categories as specified in the previous step is retrieved from the current view of the Revit Project. This will retrieve the columns, beams and infill wall from the Revit to Dynamo. Furthermore, the type name for each element modelled in Revit is retrieved and associated with the sections as shown in Figure 1-2 of Appendix I.

3. Extraction of metadata of structural members

The necessary metadata which is already attached and defined to all structural members in Revit as Type-parameter is extracted at this stage. This include geometry of the elements, concrete cover, reinforcement information and concrete strength. Dynamo codes which are developed for the extraction of reinforcement information for the specified structural elements are presented in Figure 1-3 of Appendix I. Furthermore, for the category of infill walls the extracted metadata include wall thickness, compressive strength, tensile strength, Young's modulus, specific weight and maximum shear resistance.

4. Extraction of node coordinates from the Revit Model

In the next step, the node coordinates are extracted for the structural columns. The nodes data is required in SeismoStruct for modelling of the structure. The coordinates of the columns which are extracted are aligned to its centre to generate the coordinates for both the ends of columns as shown in Figure 1-5 of Appendix I. This is done because in SeismoStruct the structural elements are drawn by connecting/joining one node to another.

5. Checker for spaces

In SeismoStruct the section and element class can't be defined if the section or element class name consists of multiple words with spacing in between. In order to solve this issue for elements having name consists of two or more words with spacing in Revit, a framework was developed which will detect the spacing in the name and put a hyphen in-between the words for the name of the element as shown in fig 1-5 of Appendix I.

6. Defining sections and element classes

In SeismoStruct to model a structure, it is required to define sections and element classes and then draw project elements according to the given element class. For this purpose, the script is developed to define sections and element classes for columns and beams which will define the same number of sections as modelled in Revit and shown in Figure 1-6 of the Appendix I. For infill walls, defining the section is not required and only element class is defined which takes the seven input properties already defined in Revit model for the infill walls.

7. Defining project elements

The project elements are defined and modelled based on the sections and element classes defined in the previous steps. This will generate and repeat the same number of project elements which are already modelled in Revit. For project elements, the input includes the element class of the structural member and non-structural infill wall, the node serial and then the coordinates of the respective nodes. The overall picture is being shown in Figure 1-7 of Appendix I.

8. Integration of the whole framework

The script made for the individual tasks such as sections, element classes and nodes etc. are then combined to a single code block which will generate the required number of sections, element classes and project elements and then combine to make a single XML file as shown in Figure 1-8 of Appendix I.

9. Defining file path for exporting to XML file

The file path for the exported XML file is defined. The file path, as well as the previously combined script, is connected to the *FileSystem.WriteText* which will write the text content specified by the path as shown in Figure 1-8 of the Appendix I. This will generate an XML file at the defined location in the operating system. A 'file written' will be shown if the file is exported successfully otherwise 'file failed'. The exported XML file format is completely compatible with SeismoStruct and can be imported for seismic analysis to SeismoStruct.

3.4. Pilot application and demonstration of feasibility

To check and understand the feasibility of the developed script and to further perform the seismic assessment in SeismoStruct, an academic example building is selected. The importance of this academic example is significant since it's a simplified building, and its behaviour is not controlled by particular issues.

3.4.1. General Description

The building considered is located in Lisbon having no seismic design provision. The building is made up of a reinforced concrete frame having a rectangular shape in-plane configuration. The structure consists of 4 storeys having each storey height is 2.8 m except the first floor, which is 3.3 m. The plan view and layout of different columns are shown in Figure 14. The geometrical properties and mechanical properties of all structural elements are presented in Table 4 and Table 5 respectively.

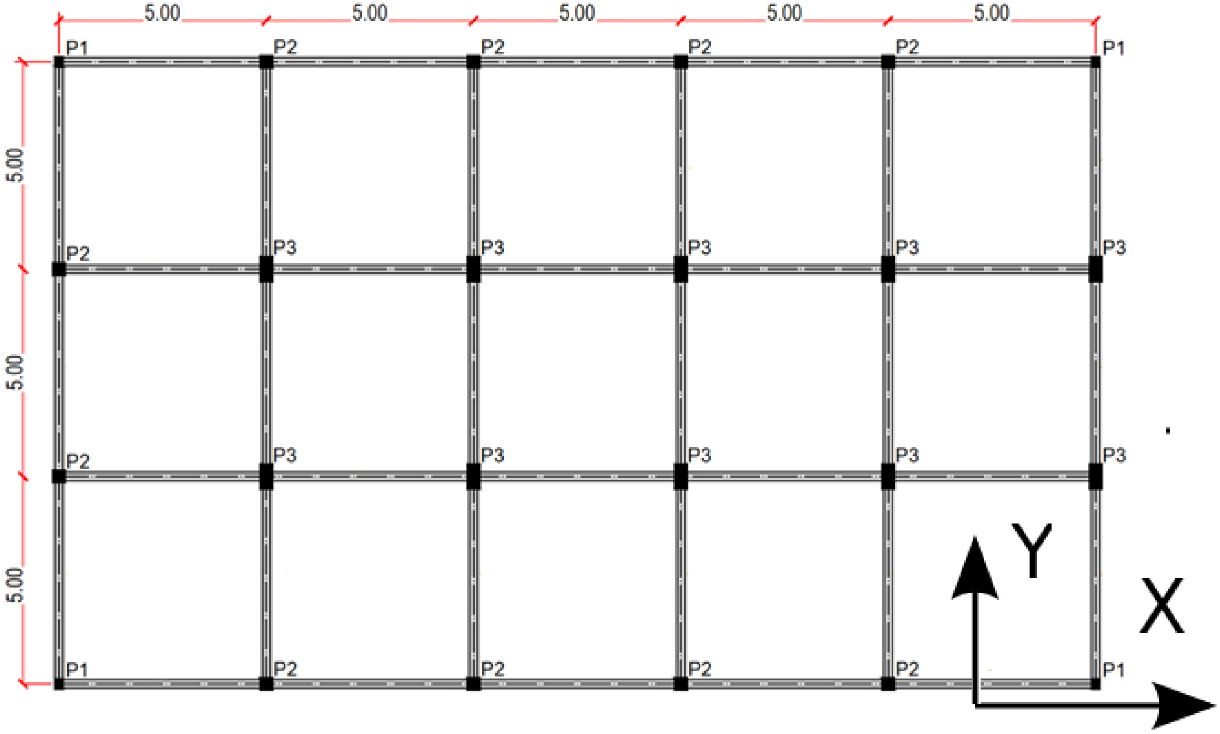


Figure 14 – Plan view

Table 4 - Geometrical properties of structural elements

<table>
<tr><th rowspan="2">Floor no:</th><th colspan="3">Columns</th><th rowspan="2">Beams</th></tr>
<tr><th>P1</th><th>P2</th><th>P3</th></tr>
<tr><td>First floor</td><td rowspan="4">0.20x0.25
LR: 4ø16
TR: ø6/0.20m</td><td>0.30x0.30
LR: 8ø16
TR: ø6/0.2m</td><td>0.30x0.60
LR: 10ø20
TR: ø6/0.25m (4-legged stirrups)</td><td rowspan="4">0.20x0.50
LR: 8ø12
TR: ø6/0.20m</td></tr>
<tr><td>Second floor</td><td>0.25x0.25
LR: 8ø16
TR: ø6/0.2m</td><td>0.30x0.40
LR: 6ø20
TR: ø6/0.25m</td></tr>
<tr><td>Third floor</td><td>0.20x0.25
LR: 4ø16
TR: ø6/0.2m</td><td>0.30x0.30
LR: 8ø16
TR: ø6/0.25m</td></tr>
<tr><td>Fourth floor</td><td>0.20x0.25
LR: 4ø16
TR: ø6/0.2m</td><td>0.20x0.25
LR: 4ø16
TR: ø6/0.25m</td></tr>
</table>

LR: longitudinal reinforcement; TR: transverse reinforcement.

For the size of columns in Table 4, the first dimension shows the size of the structural member along the x-axis, while the second dimension shows its size in the y-direction.

Table 5 – Mechanical properties and additional data

Materials	Additional data
Steel yield strength = 440 MPa	Location: Lisbon
Concrete compressive strength = 22 MPa	Ground-type: B
Concrete cover = 15 mm	Mass per Floor = 312 tons

To include the participation of masonry infill walls and study its effect on the seismic capacity of the structure, infill walls were added to the building though they weren't part of the original benchmark, they were found to be of importance for the pilot application to fully explore the framework/tools. The geometrical and mechanical properties which are considered for the infill walls are shown in Table 6.

Table 6 – Properties of infill wall

Thickness	5 cm
Compressive strength	0.66 MPa
Tensile strength	0.1 MPa
Young's modulus	1837 MPa
Shear bond strength	0.2 MPa
Specific weight	5.8 kN/m3
Maximum shear resistance	0.4 MPa

3.4.2. Modelling and execution of script/calculations

Autodesk Revit 2020 has been used to model the case study building. The structure is a four-storey office building having 5 bays in one direction and 3 bays in another direction. The modelled building has been shown in Figure 15. To perform seismic analysis in structural tool i.e. SeismoStruct, the BIM model which is already developed in Revit was exported using the developed script. This script will be able to export the BIM model in the XML format which is thoroughly readable by SeismoStruct.

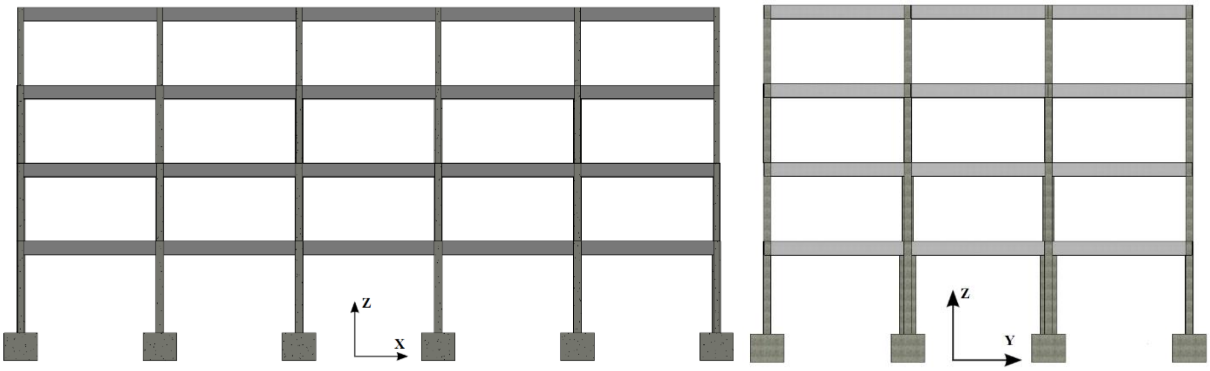
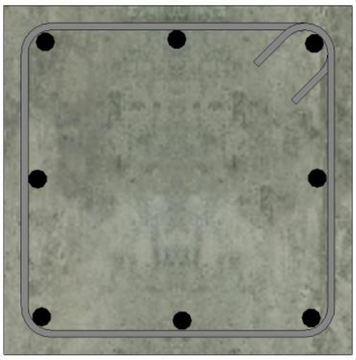


Figure 15 – Modelled structure in Revit

The model was developed in Revit according to the modelling requirements mentioned in section 3.3.3. The material properties, sizes of members, concrete cover as well as the reinforcement information are attached to the respective structural member as non-graphical information. For information purposes, a section of column P2-F1, as well as the information, attach to this column has been shown in Figure 16.



Dimensions	
Cover	0.0150 m
Depth	0.3000 m
Offset Base	0.0000 m
Offset Top	0.0000 m
Width	0.3000 m
Identity Data	
Concrete-strength	22000
yield-strength	440000

Structural	
lower-bar	3
lower-bar-dia	16
upper-bar	3
upper-bar-dia	16
side-bar	2
side-bar-dia	16
stirrup-width	2
stirrup-height	2
stirrup-dia	6
stirrup-spacing	0.200000

Figure 16 - Column section (left), size and material properties (middle), reinforcement data (Right)

The model is exported as XML file using the developed script which is then imported to SeismoStruct. The time required to execute the export depends on the performance of the operating system as well as the size of the model. For the given case study building, it takes almost 20-30 seconds to export the BIM-model to XML file format. After importing to SeismoStruct, it was found that all the geometrical properties, reinforcement information and footing are exported successfully from Revit to SeismoStruct and can be seen in Figure 17 and 18.

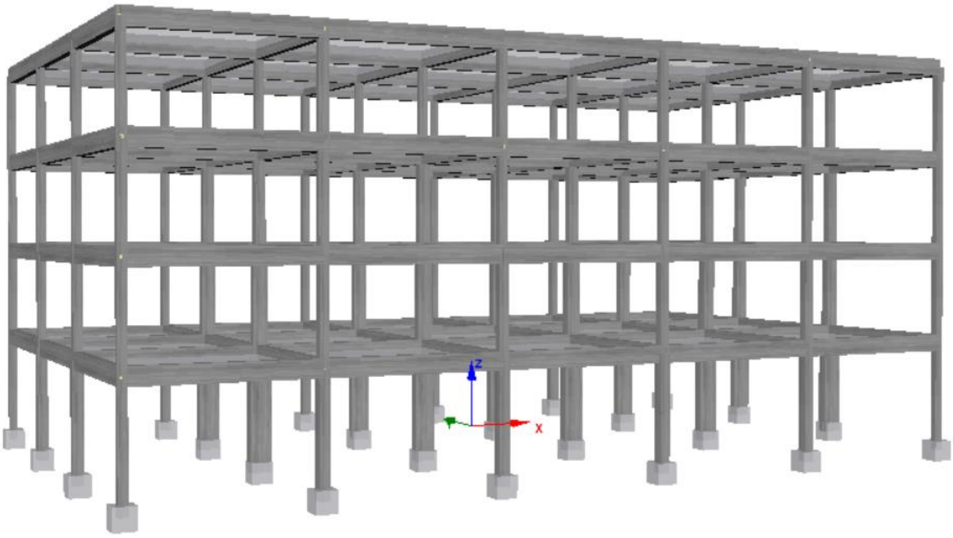


Figure 17 - Structural model imported to SeismoStruct

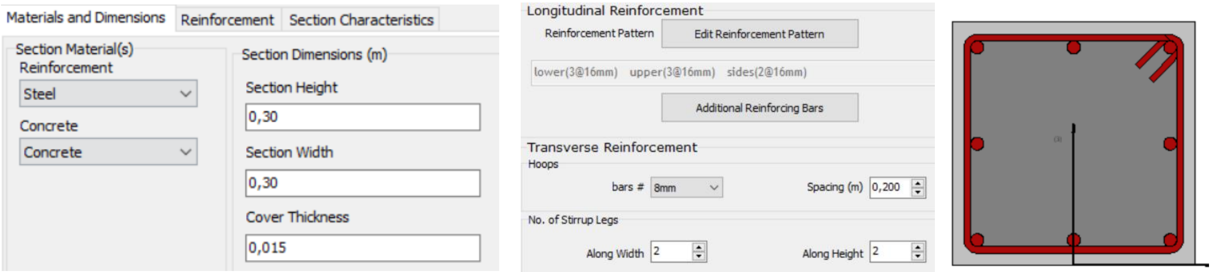


Figure 18 – Size and section materials (left), reinforcement information (middle), column section (right)

3.5. Pushover Analysis

After importing the BIM model to SeismoStruct, few additional activities need to be defined in the pre-processing before performing the pushover analysis. This includes load distribution, loading phases, defining the target displacement and code response spectrum among others. The target displacement was assumed to be 2% of the total height of the building and the capacity curve will be plotted up to that displacement. The structure is assessed at a target limit state of significant damage with a 10% probability of exceedance in 50 years showing significant damage with some residual stiffness and strength. Both triangular and rectangular lateral load distribution were assumed to perform analysis for seismic loads. The combination of permanent load and lateral loads were used to obtain the capacity curve for the building. The resulting capacity curves are shown in Figure 19 and 20 for uniform and triangular load distribution in both x and y directions, as well as showing the position of significant damage (SD) performance level, 1st column/beam shear failure and 1st column/beam yielding. The target displacement for both uniform and triangular load pattern is shown in Table 7.

Table 7 – Target displacement

Pattern of lateral load	Displacement (x) cm	Displacement (x) cm
Uniform	30	30
Triangular	30	30

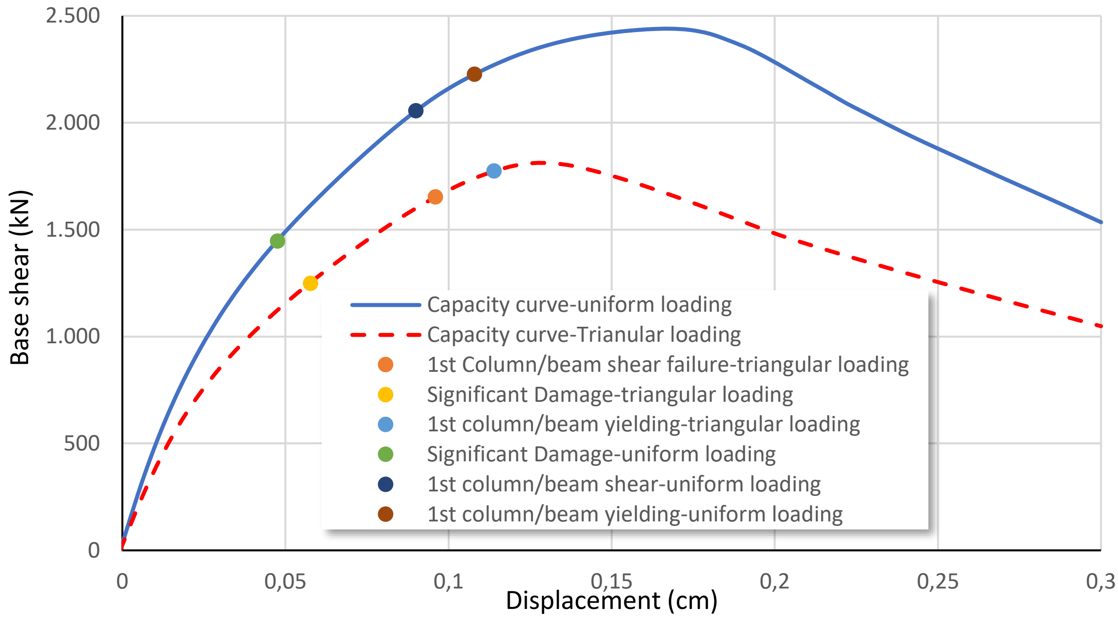


Figure 19 - Capacity curves for uniform and triangular lateral load in x-direction

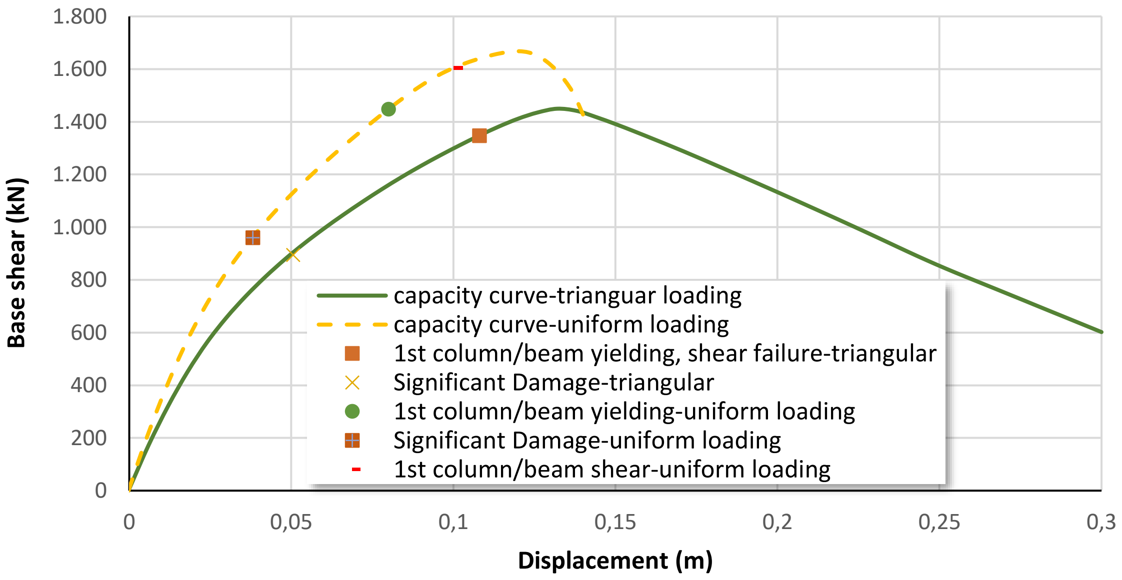


Figure 20 - Capacity curves for uniform and triangular lateral load in y-direction

The capacity curves shown in Figure 19 and 20 depicts that the building exhibits a higher capacity for a uniform lateral load configuration as compared to triangular lateral load when it is hit by earthquake either in x or y-direction. The percentage difference between the maximum base shear of the case-study building for uniform lateral load pattern is 29% and 14% higher than the triangular lateral load pattern in x and y-direction respectively. Similarly, the case-study building shows more capacity when reaches to significant damage performance level for uniform lateral load than triangular lateral load pattern by 14% and 7% in x and y-direction respectively. However, the structure has a lower target displacement for the significant damage performance level for the uniform lateral load as compared to a triangular load pattern. Moreover, by comparing Figure 19 with Figure 20 depicts that the capacity of the building in the y-direction is less than in x-direction and the building reaches to collapse at a displacement of 0.15 cm in the y-direction.

Pushover curve typically consists of an elastic and inelastic region, in which the inelastic region is the main determinant of the failure point of the model in the pushover curve. For uniform lateral load in the y-direction, the structure shows significantly less ductility as compared to the other load pattern. Furthermore, it is clear from Figure 19 and 20, that the capacity of the structure increases roughly linearly in the beginning when the building is the elastic limit. However, the slope of pushover curves started decreasing gradually with an increase in lateral load due to the yielding of structural elements.

3.6. Effect of Infill walls

Although the literature described the effect of infill walls on the seismic capacity in more detail, but its modelling is always an issue. In this case, the infill walls are modelled in Revit providing all the material properties and then exported to SeismoStruct for its contribution in the seismic capacity of the structure. This has made the job of the structural engineer simpler which will overcome the difficulties to model walls in the seismic analysis software, as well as the structural engineer, can focus more on the technical things. To understand the effect of infill wall on the structural capacity, various configurations of infill walls are applied to the structure as shown in Figure 21. In model 1, there is no infill wall either in elevation or plan. In model 2, infill walls are provided throughout the plan and elevation while in model 3, infill walls are provided throughout except level 1 (Ground floor). In model 4, infill walls are provided in an irregular pattern both in plan and elevations to understand the effect of irregularity on the seismic capacity of the structure. The location of the infill walls in model 4 is designed in irregular pattern considering more infill walls on the upper storeys than lower storeys. After modelling in Revit, these structural models are exported using the framework into XML format and then imported into SeismoStruct. All the structural columns and beams, as well as non-structural infill walls and supports, are successfully exported along with their original sections and materials which are defined earlier in Revit. After exporting, the pushover analysis of all the models shown in Figure 21 is performed. The capacity curves of all these models for both uniform and triangular load pattern are obtained which are presented in Figure 22-25. The lateral load pattern is applied in both x and y-direction to evaluate and compare the capacity of the structure for different lateral load patterns.

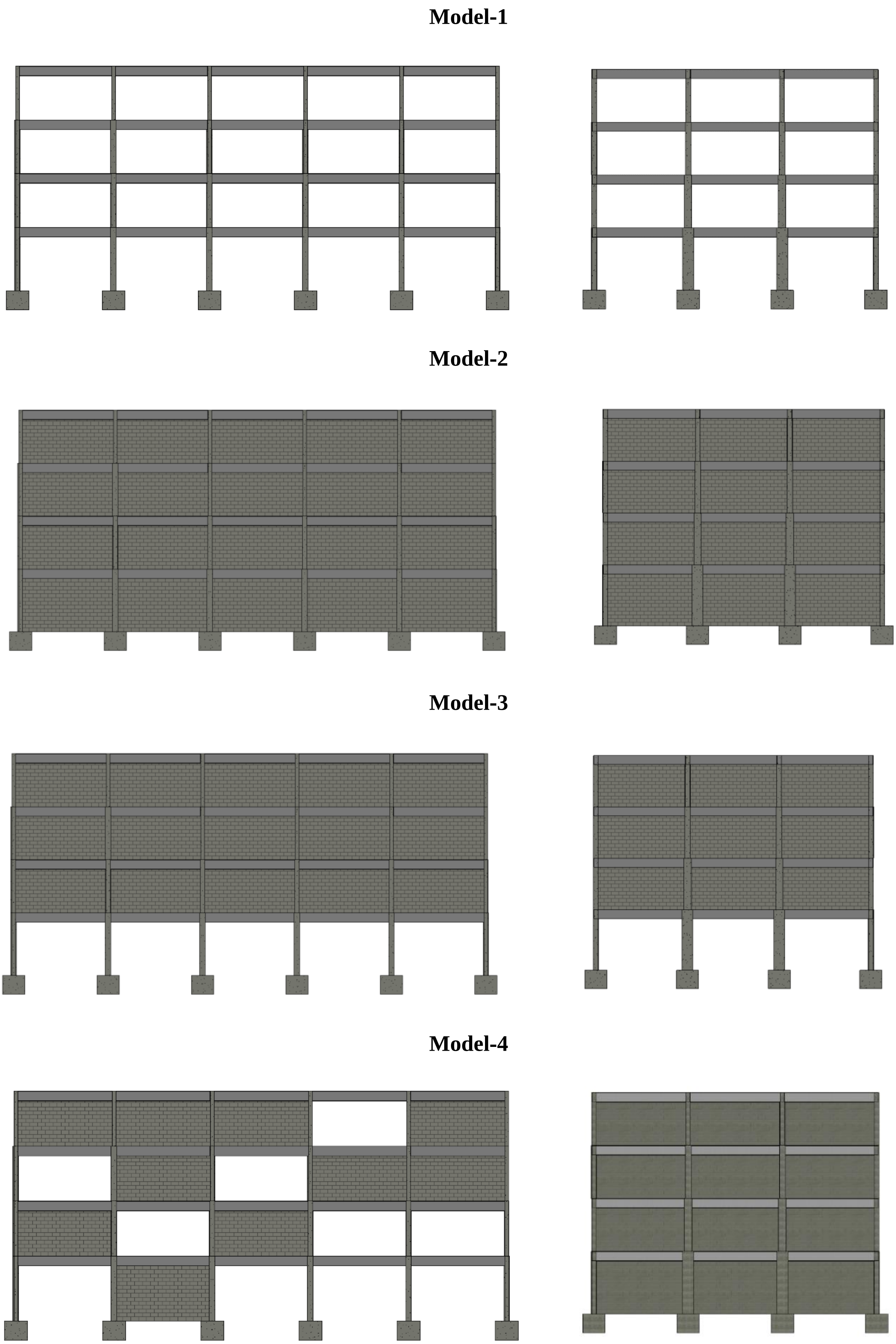


Figure 21 - Building models to be analyzed

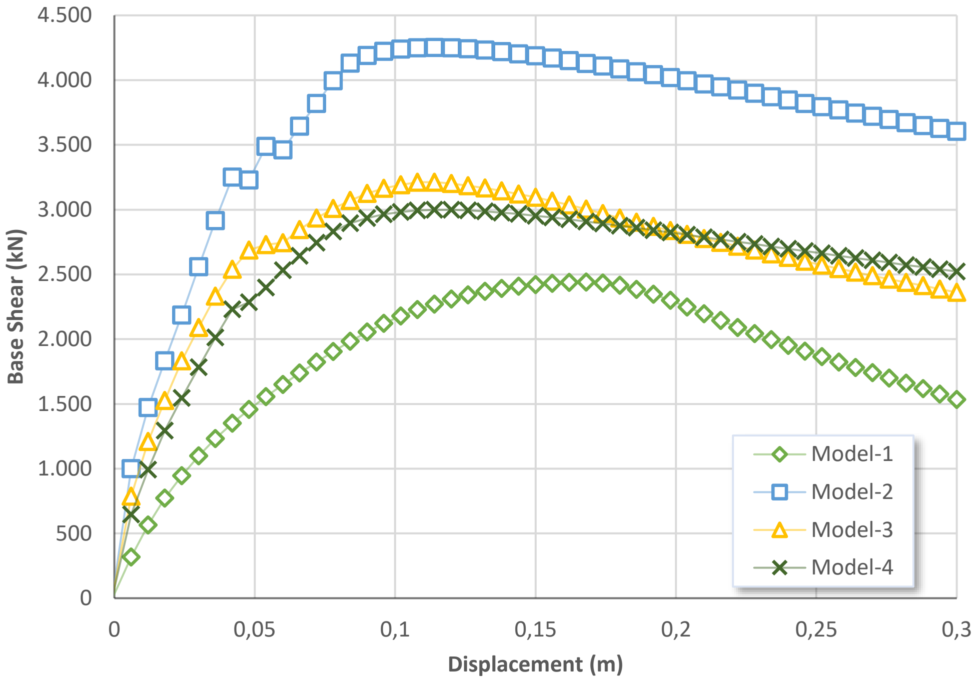


Figure 22 - Uniform lateral load in the x-direction

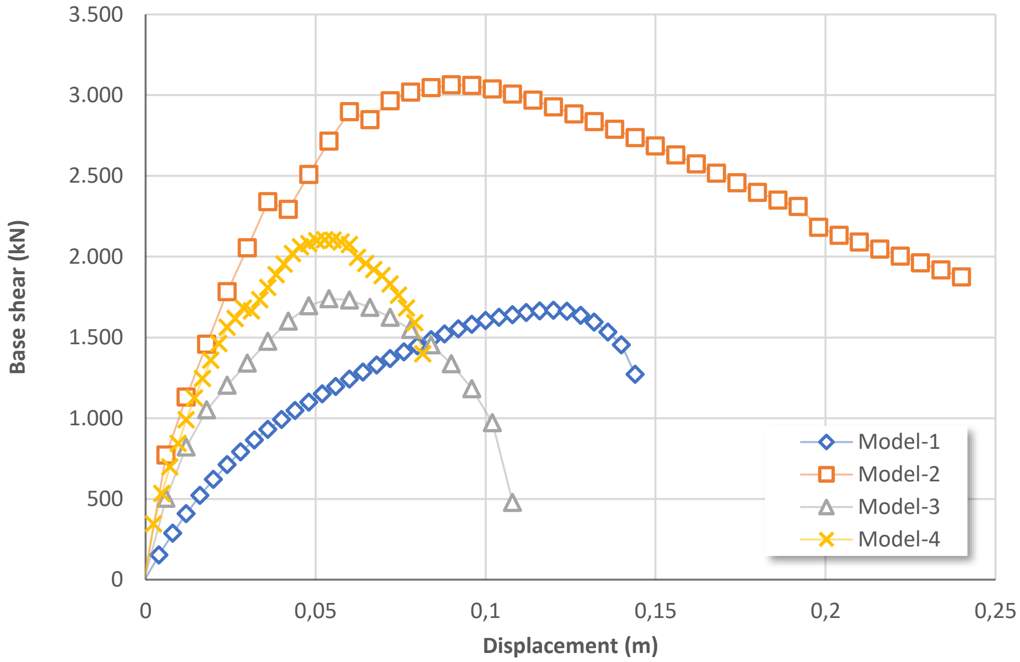


Figure 23 - Uniform lateral load in the y-direction

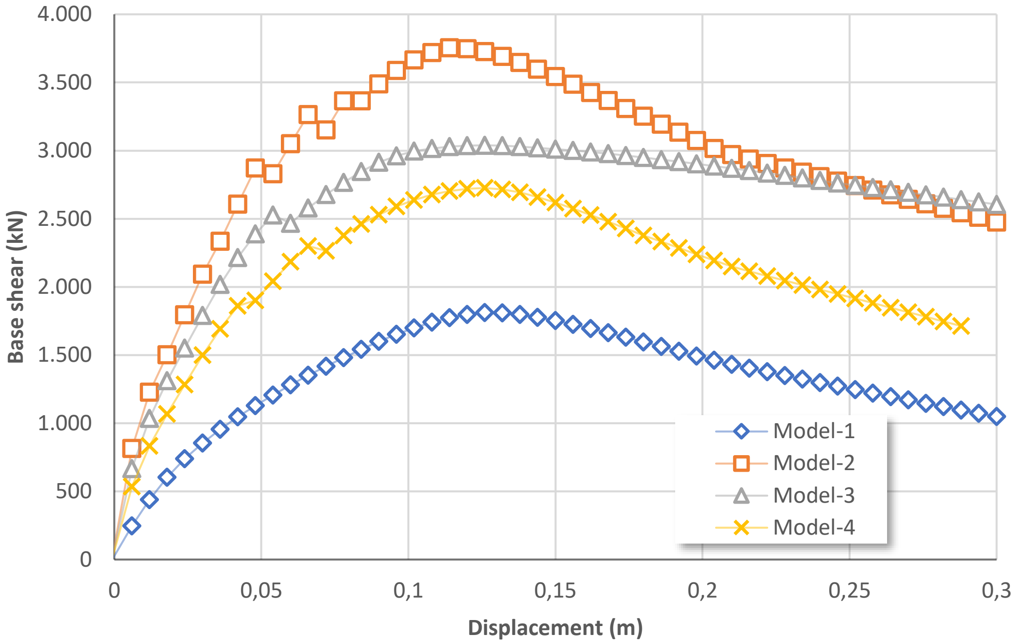


Figure 24 - Triangular lateral load in the x-direction

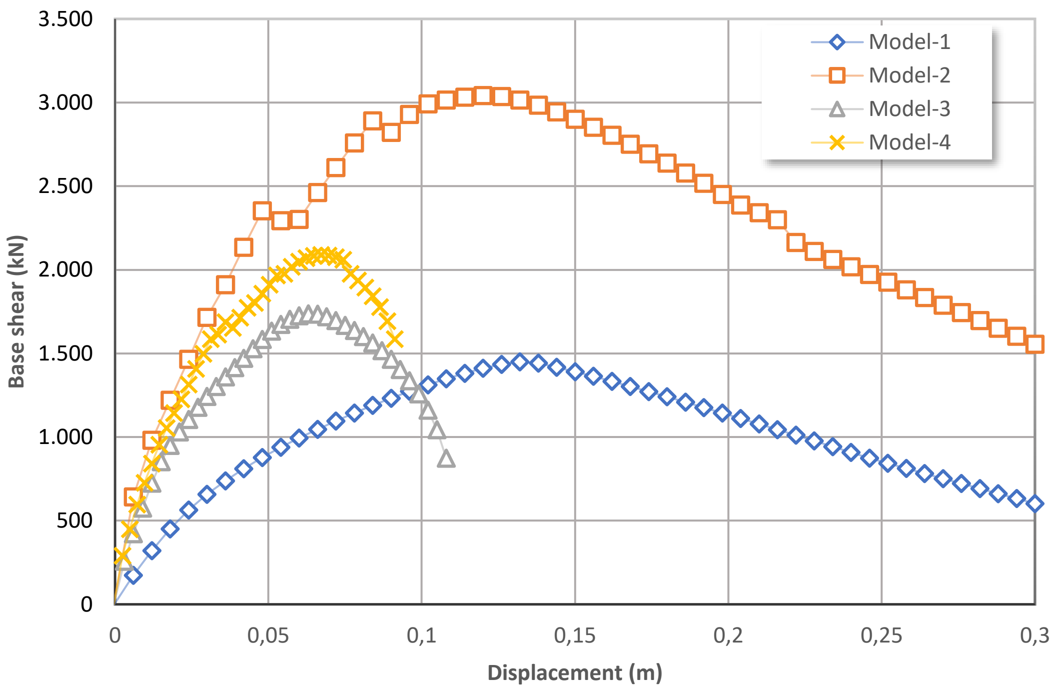


Figure 25 - Triangular lateral load in the y-direction

Table 8 – Pushover analysis

Model	Maximum base shear (kN)			
	Uniform load (x)	Uniform load (y)	Triangular load (x)	Triangular load (y)
1	2440	1668	1811	1450
2	4252	3063	3755	3041
3	3212	1740	3039	1737
4	2998	2105	2725	2089

The results shown in Table 8 demonstrate that structural infill walls have significant effects on the behaviour of the structure under seismic forces. The presence of infill walls modifies both base shear and displacement as well as enhances the integrity and stability of RC frames. However, the ductility of the structure decreases significantly in y-direction due to the addition of infill wall and the structure fail after reaching its ultimate base shear capacity. It can be seen that the structure has a higher load capacity in x-direction as compared to y-direction for both uniform and triangular lateral load pattern. Fig 22-25 compares the capacity curves for all the four building models. It can be observed that the structure with infill walls provided throughout can significantly reduce the structural damage under the seismic load. It is evident from Table 8 that y-direction is the most seismically vulnerable direction as it results in the least base shear than x-direction which is more sensitive to seismic action.

3.7. Distribution of plastic hinges

Pushover analysis can be used to identify the location of potential failure modes and weak points that the structure would undergo during a seismic event to assist in an eventual seismic strengthening/retrofitting. The failure of the structure is mainly due to the development of yielding of the structural members. The following observations can be made from the locations of flexural plastic hinges which are determined by pushover analyses at failure mode.

- For both uniform and triangular lateral load pattern, the distribution of plastic hinges is almost the same with its concentration in the bottom storeys for a structural model with infill walls.
- For uniform lateral load in the x-direction, plastic hinges are developed in the lower and middle storeys as shown in fig 26. On the other hand, for uniform lateral load in y-direction plastic hinges are concentrated in the lowermost level (Level-1).
- For triangular lateral load, the development of plastic hinges starts at the upper storeys for structure with no infill wall. However, for structure with infill walls, the plastic hinges are concentrated in lower levels as shown in Figure 27.
- It can be observed from the plastic hinge pattern for both uniform and triangular lateral load that the number of plastic hinges in the y-direction is less than the number of plastic hinges in x-direction as shown in Figure 26 and Figure 27.

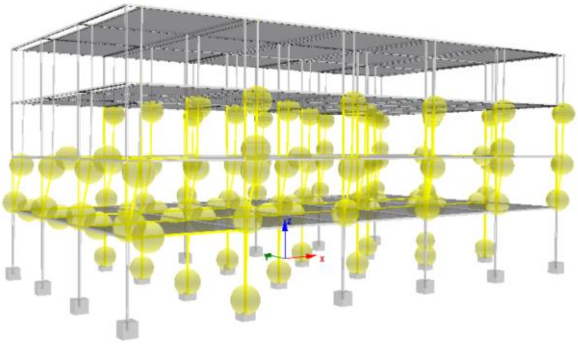
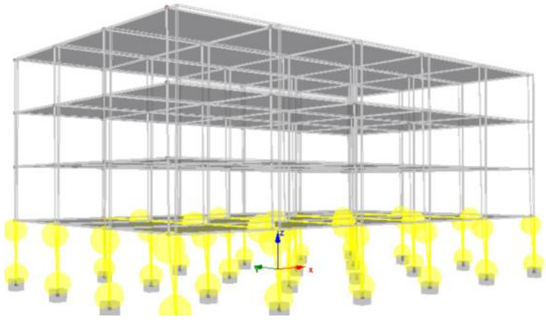
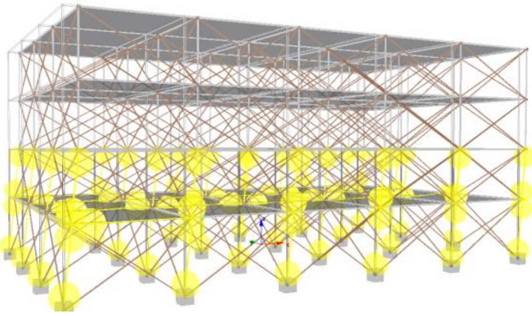
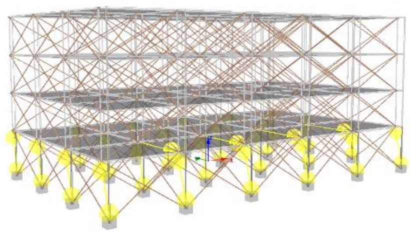
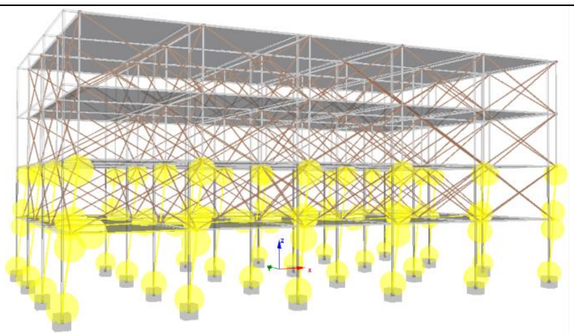
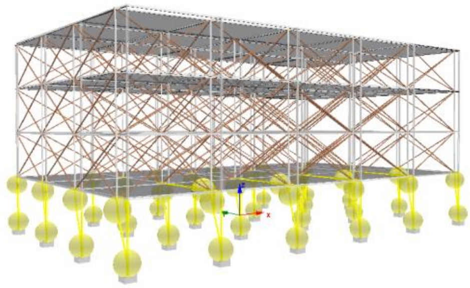
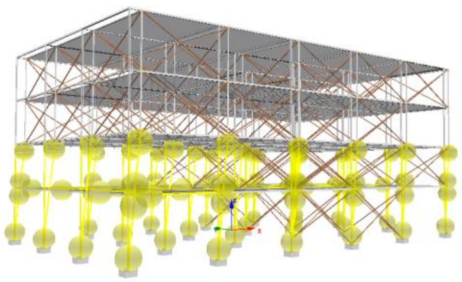
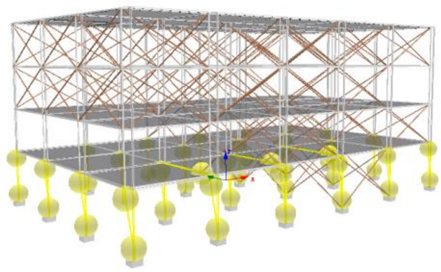
Uniform lateral load in x-direction	Uniform lateral load in y-direction
 Model-1	 Model-1
 Model-2	 Model-2
 Model-3	 Model-3
 Model-4	 Model-4

Figure 26 - Plastic hinges for uniform lateral load

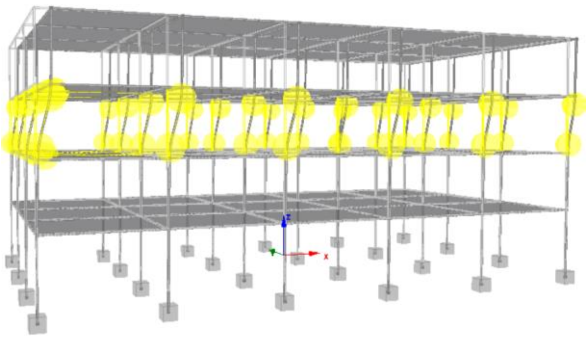
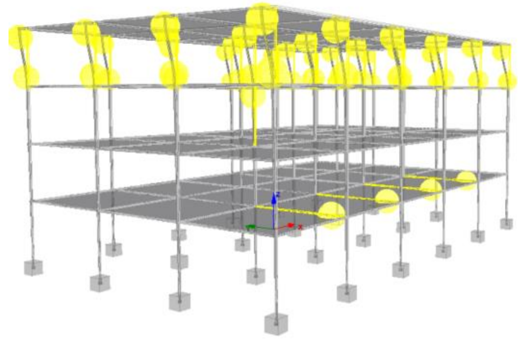
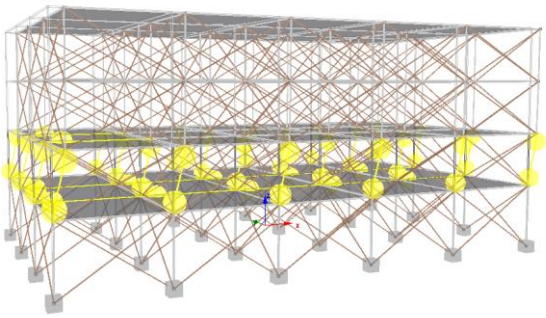
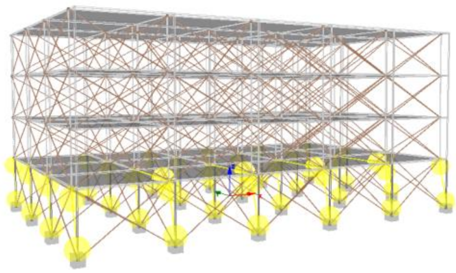
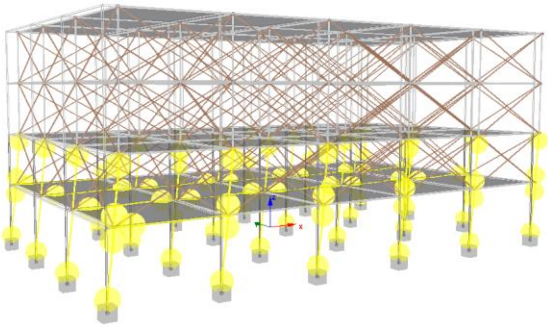
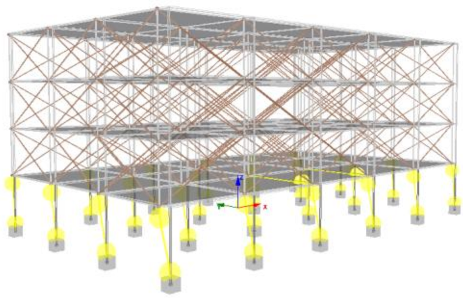
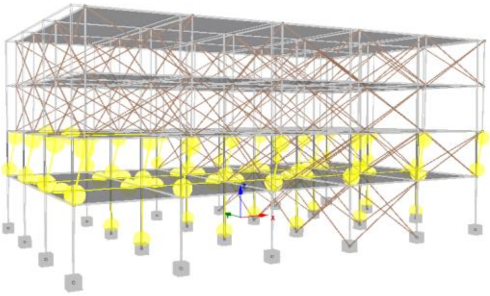
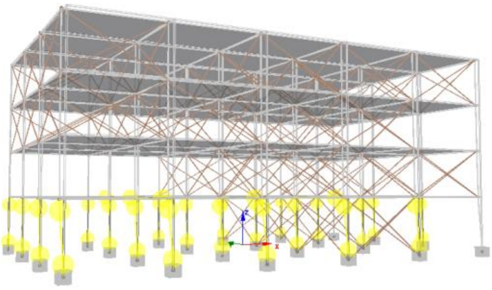
Triangular lateral load in x-direction	Triangular lateral load in y-direction
 Model-1	 Model-1
 Model-2	 Model-2
 Model-3	 Model-3
 Model-4	 Model-4

Figure 27 - Plastic hinges for triangular lateral load

3.8. Inter-storey drift

Inter-storey drift ratio is a key damage indicator on a structural level and therefore, the correct approximation of inter-storey drift ratio, as well as its distribution along with the structure's height, is very important to correctly evaluate the seismic performance. The following observations are made by studying the inter-storey drift ratio for significant damage (SD) performance level with both uniform and triangular load patterns are shown in Figure 28-29 and Figure 30-31 respectively.

- It was observed, that the inter-storey drift ratio for triangular lateral load pattern is higher both in x and y-direction as compared to a uniform load pattern.
- The inter-storey drift ratio for the structure having no infill walls is higher for both uniform and triangular lateral load than the structure models having infill walls.
- Both uniform and lateral load pattern give rather high drifts near the base of the structure and low values near the top for model-3 in comparison to other models as shown in Figure 28-31. This is due to the development of soft-storey mechanism as no infill walls are provided at the bottom-most storey of model 3.

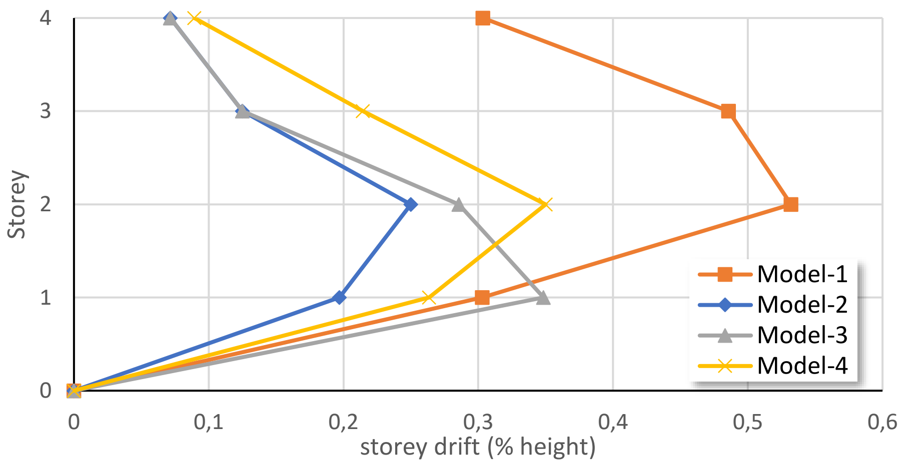


Figure 28 - Storey drift for uniform lateral load pattern in x-direction

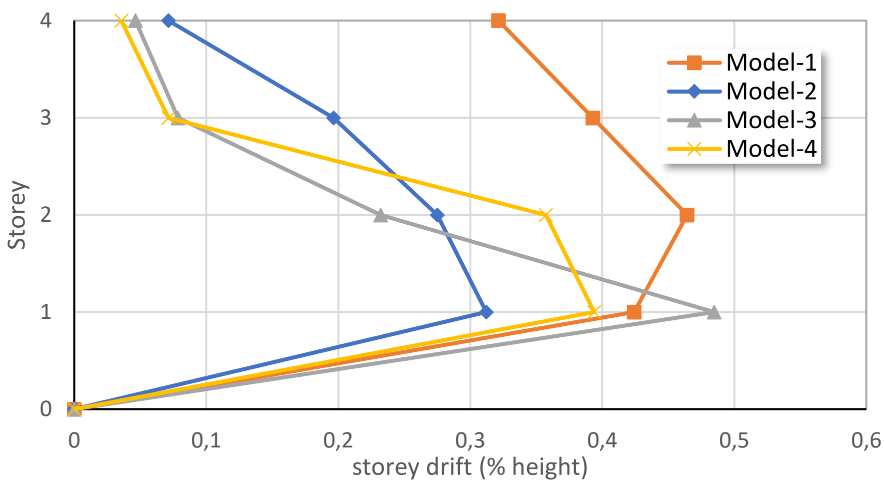


Figure 29 - Storey drift for uniform lateral load pattern in y-direction

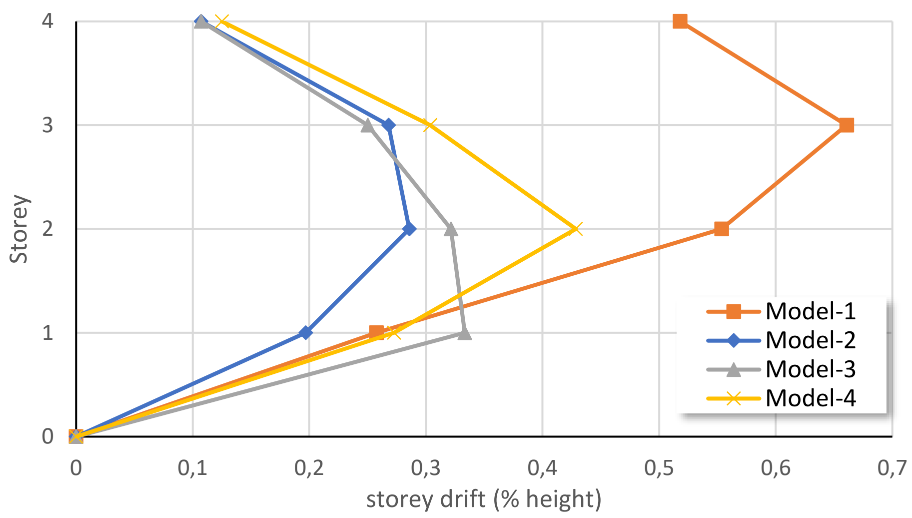


Figure 30 - Storey drift for triangular lateral load pattern in x-direction

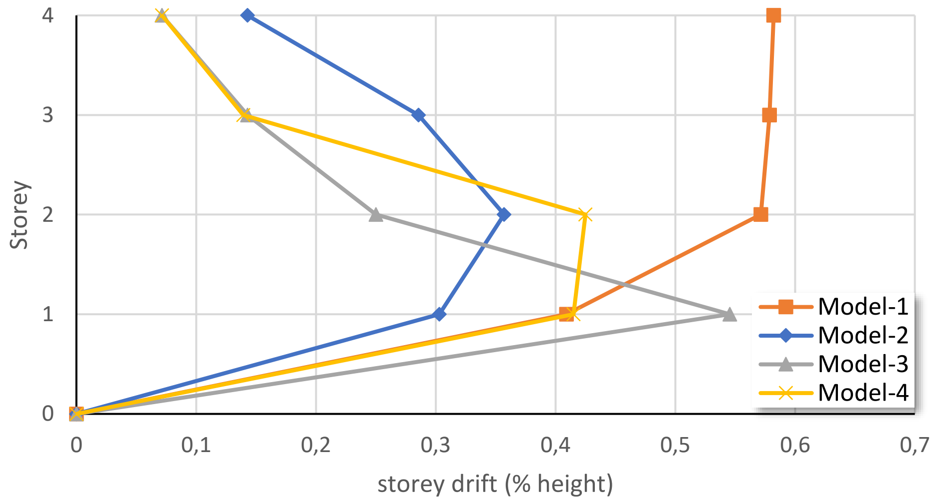


Figure 31 - Storey drift for triangular lateral load pattern in y-direction

3.9. Determination of target displacement

The target displacement of the benchmark building is calculated using the N2 method considering the Type-1 spectra which correspond to a high seismicity hazard. The surface wave magnitude for Type-1 spectra is considered to be more than 5.5.

Sd (T) - TYPE 1 earthquake - HORIZONTAL Elastic Response Spectrum

The analysis of a 4-storey regular RC frame structure is performed using the N2 method. There are four and six frames in the transversal and longitudinal directions respectively. The frame spans are 5 m in both directions. The total height of the building is 11.5 m and the first natural period of the building is T_1= 0.47 seconds in the x-direction.

3.9.1. Data

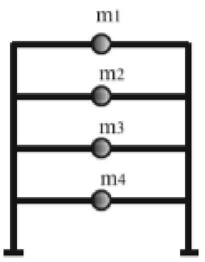
Some of the structural data is presented in Table 9 and Table 10.

Table 9 – Seismic data for the structure

Shape of the response Spectrum	Type 1 (High Seismicity)
Direction (Seismic Component)	Horizontal
Ground Type	B
Importance class	B
Behavior coefficient (q)	1.5
Importance Factor	1
Damping ratio	5%
Peak Ground Acceleration (α_{gR})	1.5 m/sec^2
Building location	Lisbon
Soil factor (s)	1.29
Lower limit of the period of the constant spectral acceleration branch (T_B)	0.1 sec
Upper limit of the period of the constant spectral acceleration branch (T_c)	0.6 sec
Value defining the beginning of the constant displacement response range of the spectrum (T_D)	2 sec

Table 10 – Calculation of effective mass

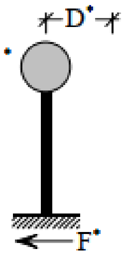
floor	mass per floor (tons)	Ø	m. Ø	m.Ø^2	Lateral Force (kN)
1	312	0.25	78	19.5	50
2	312	0.5	156	78	100
3	312	0.75	234	175.5	150
4	312	1	312	312	200
	m*		780 tons		



Pushover analysis is performed using the distribution of lateral forces as shown in Table 15, which gives the relation between base shear and displacement at the top of the building as shown in Figure 32.

3.9.2. Equivalent SDOF model

a. Determination of Mass = $m^* = \Sigma\, m_i \,.\, Ø_i$



where m_i is the mass in the i-th storey. Displacements are normalized in such a way that $Ø_n = 1$, where n is the control node and denotes the roof level.

$$m^* = 780 \text{ tons} = 7650 \text{ kN}$$

b. Conversion of MDOF quantities to SDOF

$$\Gamma = m^* / \Sigma\, m.Ø^2 = 1.33$$

The natural period of the structure is be approximated by the following expression for buildings with heights up to 40 m:

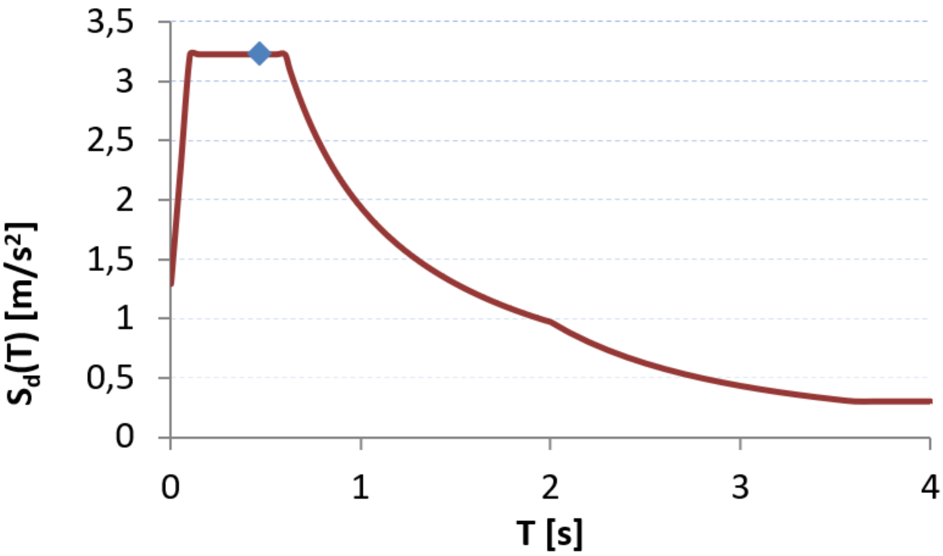
$$T_1 = C_t .\, H^{3/4}$$

Where C_t is 0.075 for moment resistant space concrete frames

And H is the height of building from the foundation in m.

$$H = 11.5\text{m}$$

$$T_1 = 0.47 \text{ sec}$$



3.9.3. Approximation of elastoplastic force-displacement relationship

The yield force F_y, which represents the ultimate strength of the idealized system, is equal to the base shear force at the formulation of the plastic mechanism.

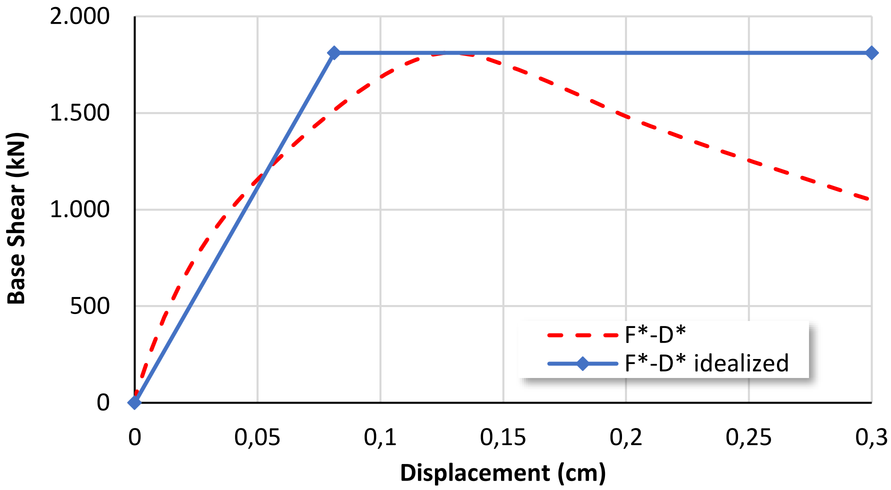


Figure 32 - Capacity curves

From Figure 33, the yield strength and its corresponding yield displacement are given below,

$$F_y^* = 1811.16 \text{ kN}$$

$$D_y^* = 0.0813 \text{ m}$$

c. Determination of the period of the idealized equivalent SDOF system:

The period T^* of the idealized equivalent SDOF system is determined by:

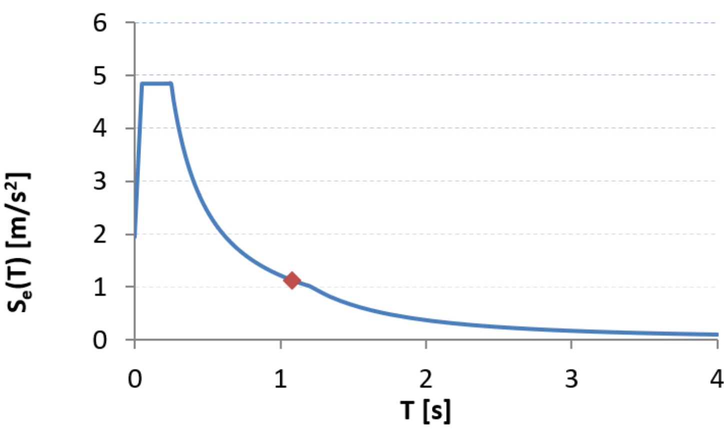
$$T^* = \frac{2\pi\sqrt{m^*.Dy^*}}{Fy^*}$$

$$T^* = 1.08 \text{ sec}$$

d. Determination of the target displacement for the equivalent SDOF system

The target displacement of the structure with period T^* and unlimited elastic behaviour is given by:

$$d_{et}^* = \frac{Se(T^*)}{(2*\pi)^2}.(T^*)^2$$



where $Se(T^*)$ is the elastic acceleration response spectrum at the period T^*.

$$Se(T^*) = 1.12 \text{ m/sec}^2$$

$$\text{So, } d_{et}^* = 0.033 \text{ m}$$

For the determination of the target displacement d_t^x for structures in the medium and long period ranges the following expression is used.

As $T^* > T_c$ (medium and long-period range)

$$\text{So, } d_t^* = d_{et}^* = 0.033 \text{ m}$$

e. Determination of the target displacement for the MDOF system:

The target displacement of the MDOF system is given by

$$d_t = \Gamma .\ d_t^*$$

$$d_t \quad = 0.044\text{m} = 4.4 \text{ cm}$$

3.9.4. Summary

The target displacement computed using the manual calculations is compared with the target displacement calculated using SeismoStruct. The software results show a close proximity to the hand calculations of the target displacement. The target displacement calculated using SeismoStruct is 4.76 cm which is 7% more than the displacement measured using the manual calculations.

4. SEISMIC EVALUATION OF CASE-STUDY BUILDING USING THE DEVELOPED FRAMEWORK

4.1. Introduction

The main purpose of this chapter is to apply and evaluate the developed script for a real building selected by Newton, located in Lisbon, which has been the subject of analysis recently. The building is however slightly adapted because of the fact that the integrated framework shown in Chapter 3 does not yet have the capacity to handle shear walls. This chapter further demonstrates the viability of the implemented features in the framework, while also discussing its limitations. Two distinct situations are studied: with and without infill walls. This allows some preliminary conclusions to be taken regarding the usefulness of this feature in achieving more cost-effective potential decisions on retrofitting.

4.2. Structural details for the case study building

The case-study building is part of a real and modified form of an existing building which is located in Lisbon and was built in 1979. The building is a four-storey framed structure with two bays in one direction while six bays in another direction. Different sized columns and beams were used on the same floor have a distinct section with different reinforcement pattern. Moreover, this case study building is irregular both in plan and elevation, which makes its structural behaviour more complex than the pilot building being explained in Chapter 3. The different sections of this case-study buildings are provided and are shown in Figure 33, 34 and 35 respectively. In this case, the structure is a reinforced concrete frame structure whose geometrical and reinforcement information are presented in Table 11. The height of the ground storey is 3.93m, while the height of the middle storeys (level 2 and level 3) remains the same i.e. 2.68m. The height of the top storey is 2.85m. The concrete class used for the columns and beams in the case study building is C16/20 while the steel grade is A400. Two model cases will be studied in this chapter: one without infill wall and one with infill wall. The infill walls properties presented in Table 12 are taken from the literature which will be used in the second case in the model with the infill wall.

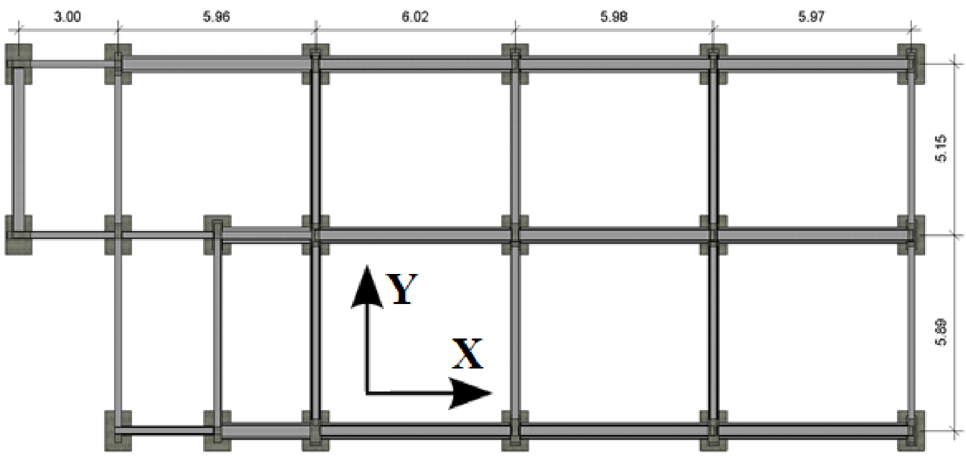


Figure 33 - Plan of the case-study building at Level 1-3 (Units: m)

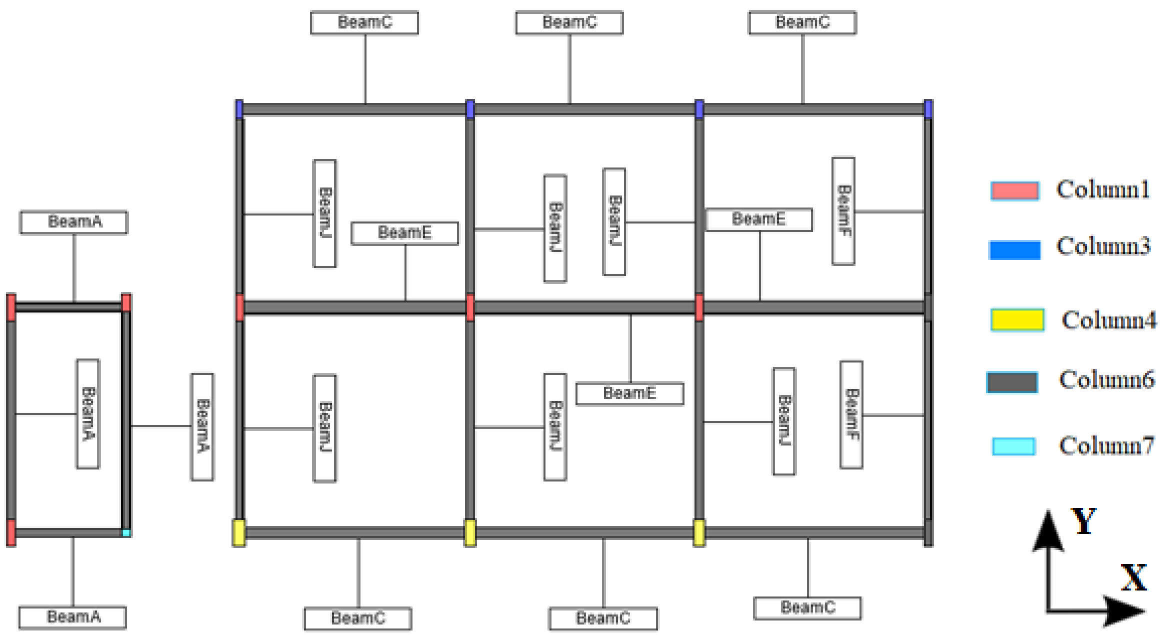


Figure 34 – Plan of the case-study building (Level – 4)

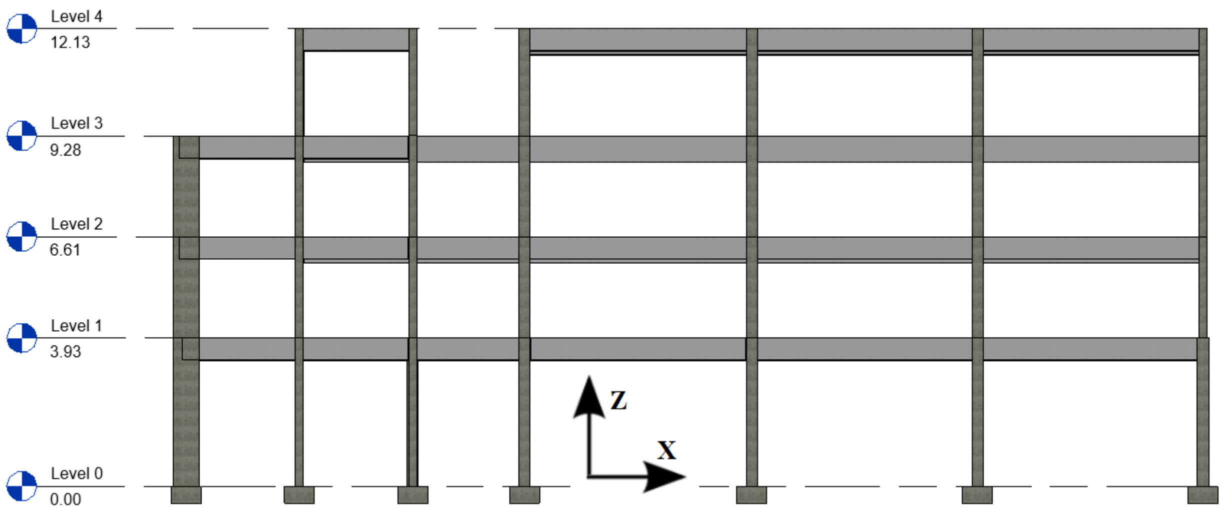


Figure 35 - Elevation of the case-study building

In Figure 35, the rightmost column has a different cross-section in the first floor than the columns cross-sections on the subsequent floors. The change in cross-section is made around the centre of the column itself to generate a common node for both the columns in SeismoStruct. For the size of columns defined in Table 11, the first dimension shows the size of the structural member along the x-axis, while the second dimension shows its size in the y-direction. In case of beams, the first dimension is the width of the beam (either in x or y-direction) while the second dimension shows the total depth of the beam (in the z-direction)

Table 11 – Structural data for the existing building

Beams			Columns		
	Size (cm*cm)	**Reinforcement data**		**Size (cm*cm)**	**Reinforcement data**
Beam-A	22*60	LR: 3ø25 LR: 3ø20 TR: ø6/0.20m	**Column-1**	22*70	LR: 4ø20 LR: 6ø16 TR: ø6/0.15m
Beam-B	50x60	LR: 6ø16 LR: 5ø16 TR: ø6/0.20m	**Column-2**	30x90	LR: 20ø25 TR: ø8/0.20m(4-legged stirrups)
Beam-C	30x60	LR: 5ø25 LR: 3ø16 TR: ø6/0.20m	**Column-3**	20x50	LR: 8ø16 TR: ø6/0.20m
Beam-D	20x60	LR: 2ø16 LR: 2ø20 TR: ø6/0.20m	**Column-4**	30x70	LR: 16ø25 TR: ø8/0.25m(4-legged stirrups)
Beam-E	35x70	LR: 5ø25 LR: 5ø20 TR: ø8/0.20m	**Column-5**	20x90	LR: 12ø25 TR: ø8/0.17m
Beam-F	20x75	LR: 3ø25 LR: 2ø16 TR: ø6/0.20m	**Column-6**	20x70	LR: 10ø25 TR: ø8/0.17m
Beam-G	28x60	LR: 3ø12 LR: 3ø12 TR: ø6/0.20m	**Column-7**	22x22	LR: 4ø16 TR: ø6/0.20m
Beam-H	30x60	LR: 4ø20 LR: 4ø20 TR: ø6/0.20m			
Beam-I	25x45	LR: 2ø25 LR: 3ø12 TR: ø6/0.20m			
Beam-J	22x75	LR: 3ø25 LR: 3ø20 TR: ø6/0.20m			

LR: longitudinal reinforcement; TR: transverse reinforcement (All of the transverse reinforcement mentioned above is 2-legged stirrups except where mentioned)

Table 12 - Properties of the infill wall

Thickness	15 cm
Compressive strength	0.66 MPa
Tensile strength	0.1 MPa
Young’s modulus	1837 MPa

4.3. Interoperability check for existing building

For the interoperability check and further seismic assessment, the case study building was modelled in Autodesk Revit and the information regarding material properties, geometrical properties and reinforcement information is attached to the structural elements following the guidelines defined in Chapter 3. The 3D model of the case-study building after being modelled in Autodesk Revit is shown in Figure 36.

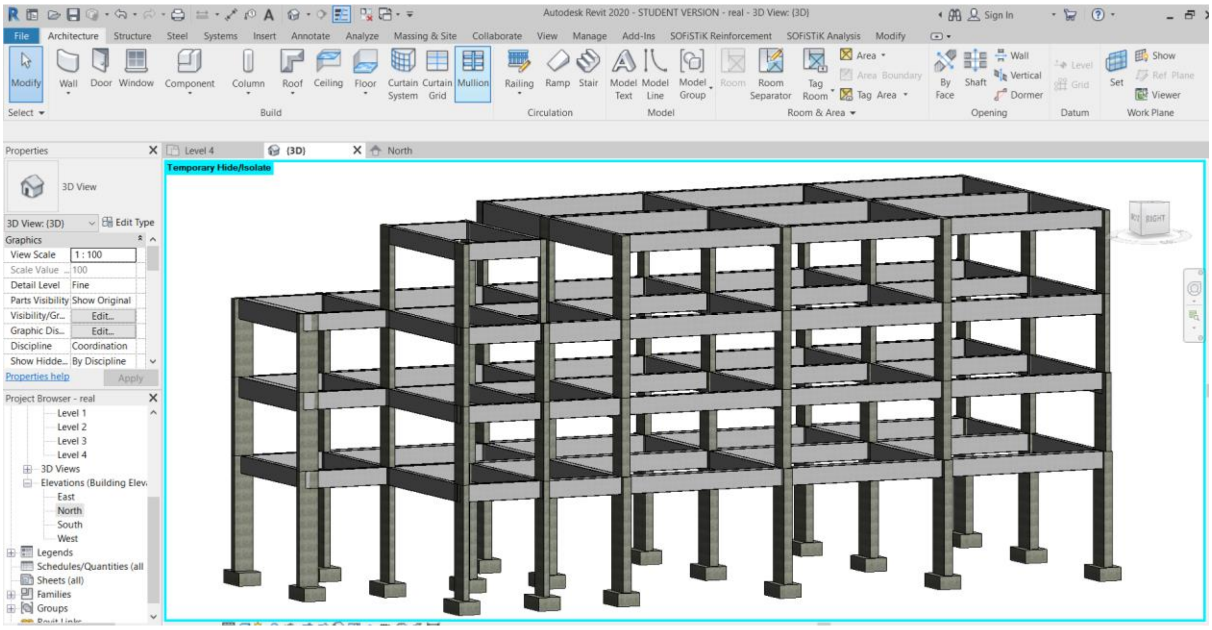


Figure 36 - 3D model in Revit

The modelled building was exported using Dynamo player with the already developed script. This has generated an XML file which was in turn imported to SeismoStruct. The resulting 3D model of the building in SeismoStruct is shown in Figure 37. At first glance, all geometry was exported, and further detailed verifications allowed to confirm the successful geometric export. The time required to model the case study building and attaching all the relevant information depends on the modelling capabilities of the individual and availability of all the data at a ready-to-model state. However, for a person with basic to intermediate skills, it should take just a few hours to model the structure as well as attach all the relevant data and export the model to SeismoStruct. In this case, the time of modelling is strongly reduced as compared to the full modelling of the rebars in the BIM authoring tool. Furthermore, chances of error in modelling are likely to be reduced because of the strong reduction in the necessary operations.

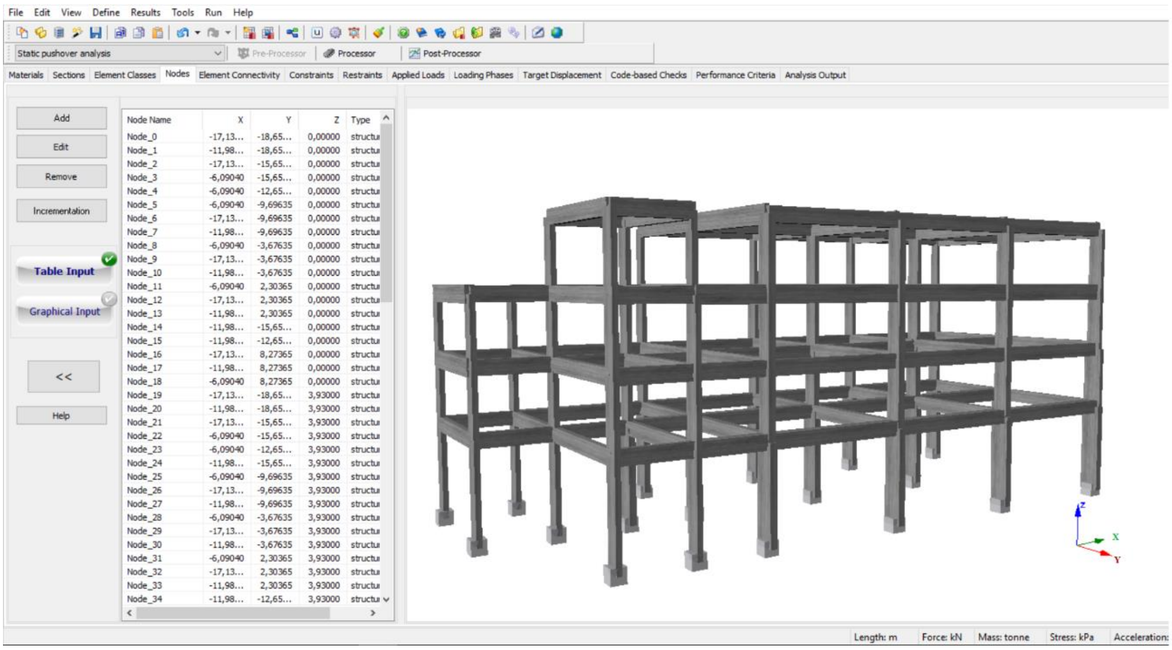


Figure 37 - 3D view of the building after exported to SeismoStruct

For the purpose of comparison, the section, concrete cover and reinforcement information attached to the structural members in the Revit model are compared to the cross-section of the relevant structural member in SeismoStruct. The comparison of the sections in both software shows that the interoperability was considered 100% successful at graphical and non-graphical levels as the structural dimensions and reinforcement data before and after exporting remains the same in both tools. This will allow us to perform the seismic analysis of the case-study building after defining a few parameters in SeismoStruct. Table 13 provides the list of activities to be performed in SeismoStruct before starting the processer to run the analysis. In Table 13, three limit states can be defined which include Damage Limitation, Significant Damage and Near Collapse. The limit states which are defined in the target displacement are then used in the code-based checks and performance-based checks.

Table 13 – Parameters to be defined in SeismoStruct

Parameters	Description
Constraints	The constraint type, the associated master node, the restrained DOFs and the slave nodes are identified for each floor.
Applied loads	Both permanent and incremental loads are defined and applied on the structural elements and nodes respectively.
Loading Phases	The number of steps for analysis and target displacement is defined.
Target displacement	The limit states, spectral acceleration, ground type, importance class and damping are defined.
Code-based checks **Performance-based checks**	Both yielding and shear failure criteria are defined for structural elements. Structural Code and Limit States are defined as well.

The time required to perform all these tasks in SeismoStruct depends on the size of the structural model. For the case-study building, the time spent to do all the tasks as shown in Table 13 didn't take more than 20 minutes.

4.4. Seismic assessment of the case-study building

The seismic assessment of the case study building is performed in SeismoStruct using pushover analysis. The permanent load is applied on all the beams while nodal loads are applied on the nodes (beam-column joints) in the y-direction. The analysis is performed only in the y-direction because of the fact that it is the weakest direction and hence more vulnerable to seismic risk. The control node for pushover analysis is the topmost node which is in the opposite side of the building on which the lateral load is applied. The analysis is performed for a target displacement of 25 cm in the y-direction (which is almost 2% of the total height of the building) for both uniform and triangular loading pattern. Moreover, a total number of 50 steps are selected for achieving the above-mentioned target displacement. The capacity curves which are obtained after the analysis is shown in Figure 38. The pushover curve is further used to identify the location of potential plastic hinges which shows the weak points in the structure during an earthquake. The capacity curve shows that the structure will observe significant damage at a base shear of 1720 kN and 1600 kN when the structure top displacement reaches to 1 cm and 1.3 cm for uniform and triangular lateral loading respectively.

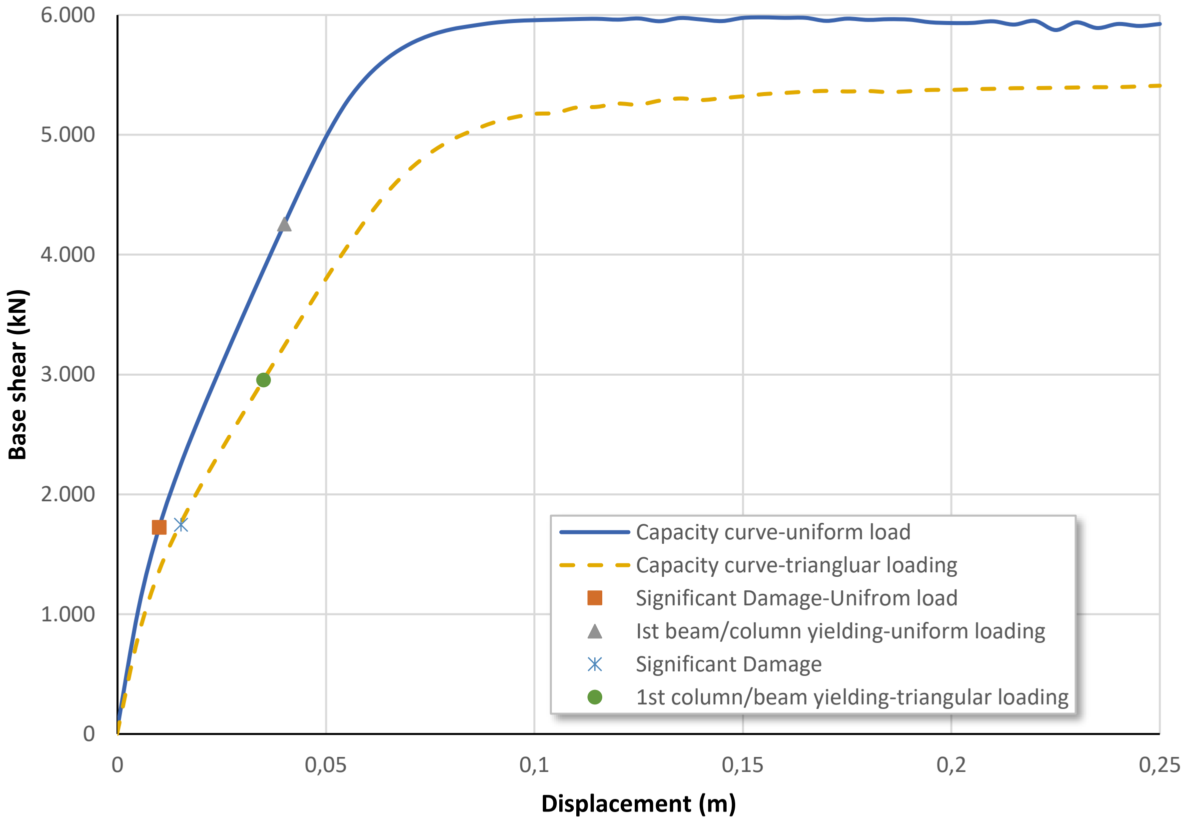


Figure 38 - Capacity curves of the case-study building in x-direction

4.5. Alternate scenario with infill wall

The effect of infill walls on the seismic capacity of the structures has been studied in the literature but is rarely applied in the real scenarios during the seismic assessment and design. In this case, the infills walls are modelled in Revit providing all the relevant material properties. The properties of the infill wall are provided in Table 12, while the configuration of infill walls which are marked in red is shown in Figure 39. For simplification, no openings were provided in the infill walls and are therefore recommended to extend this work in the future by providing openings for doors and windows etc.

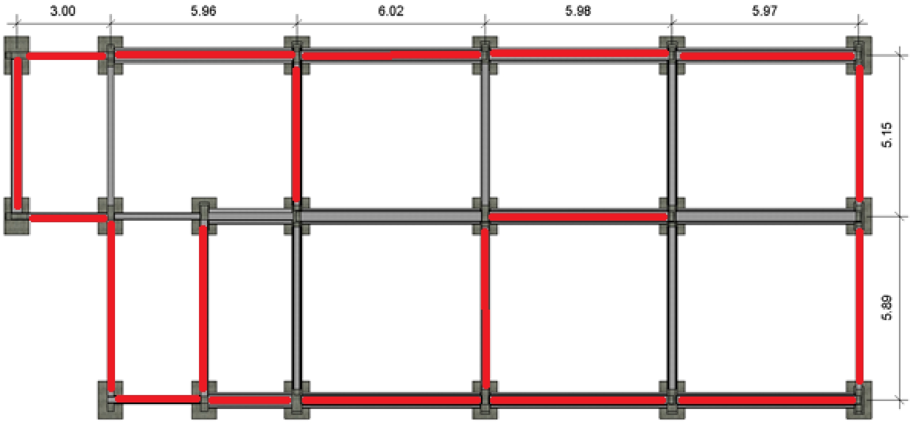


Figure 39. Configuration of infill walls

In this configuration, the infill walls are extended throughout all the floors and are provided at the exterior side of the building as shown in Figure 40. Few infills wall are modelled in the interior as well to serve as a partition wall between the rooms. After modelling in Revit, the structural model is exported using the developed framework into XML format and then imported into SeismoStruct which is shown in Figure 41. Few additional activities need to be defined in the pre-processing before performing the pushover analysis which includes load distribution, loading phases, defining the target displacement and code response spectrum among others. The pushover analysis is performed for the uniform and triangular lateral load pattern and the resulting capacity curves are then compared as shown in Figure 42.

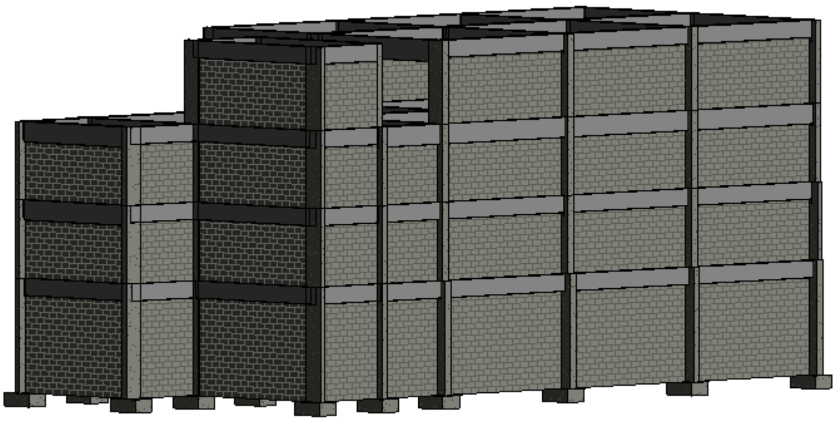


Figure 40 - Structural model in Revit

Figure 41 - Structural model after imported in SeismoStruct

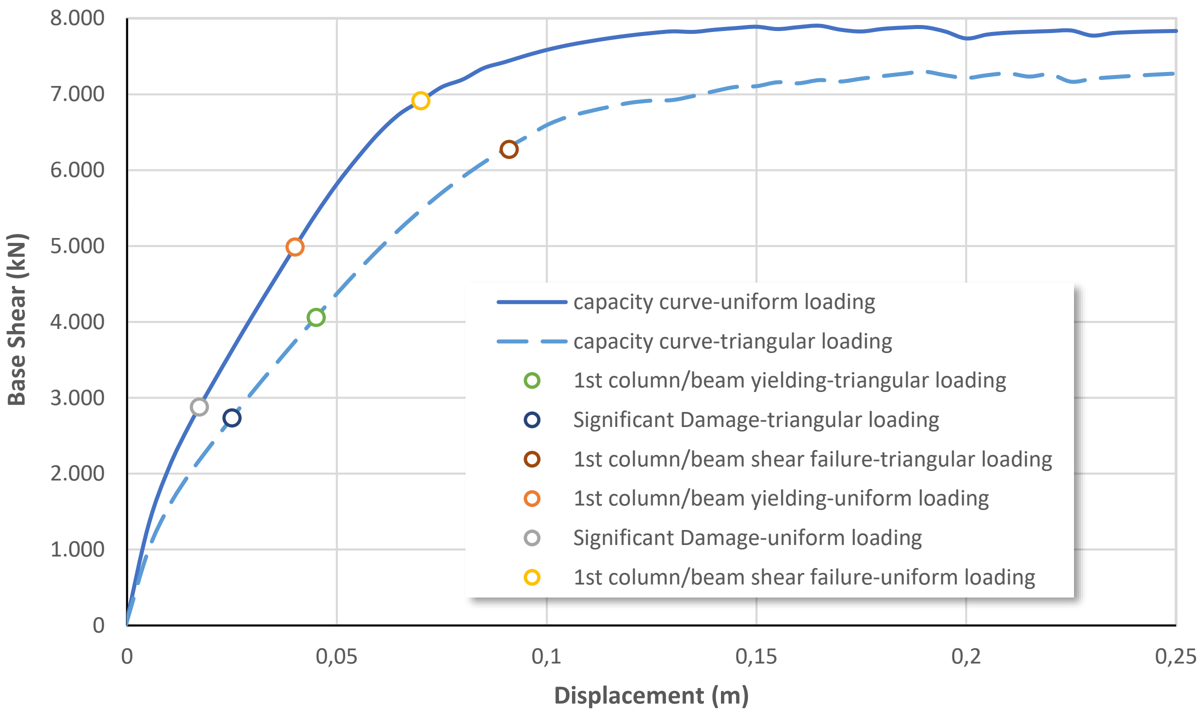


Figure 42 – Capacity curves of the case-study building having infill walls

Figure 43 compares the potential plastic flexural hinges that are developed due to uniform and triangular lateral load pattern for a bare frame structure and structure with infill walls. It shows that for both uniform and triangular load pattern, the development of plastic hinges is almost the same i.e. plastic hinges are developed throughout all storeys at failure.

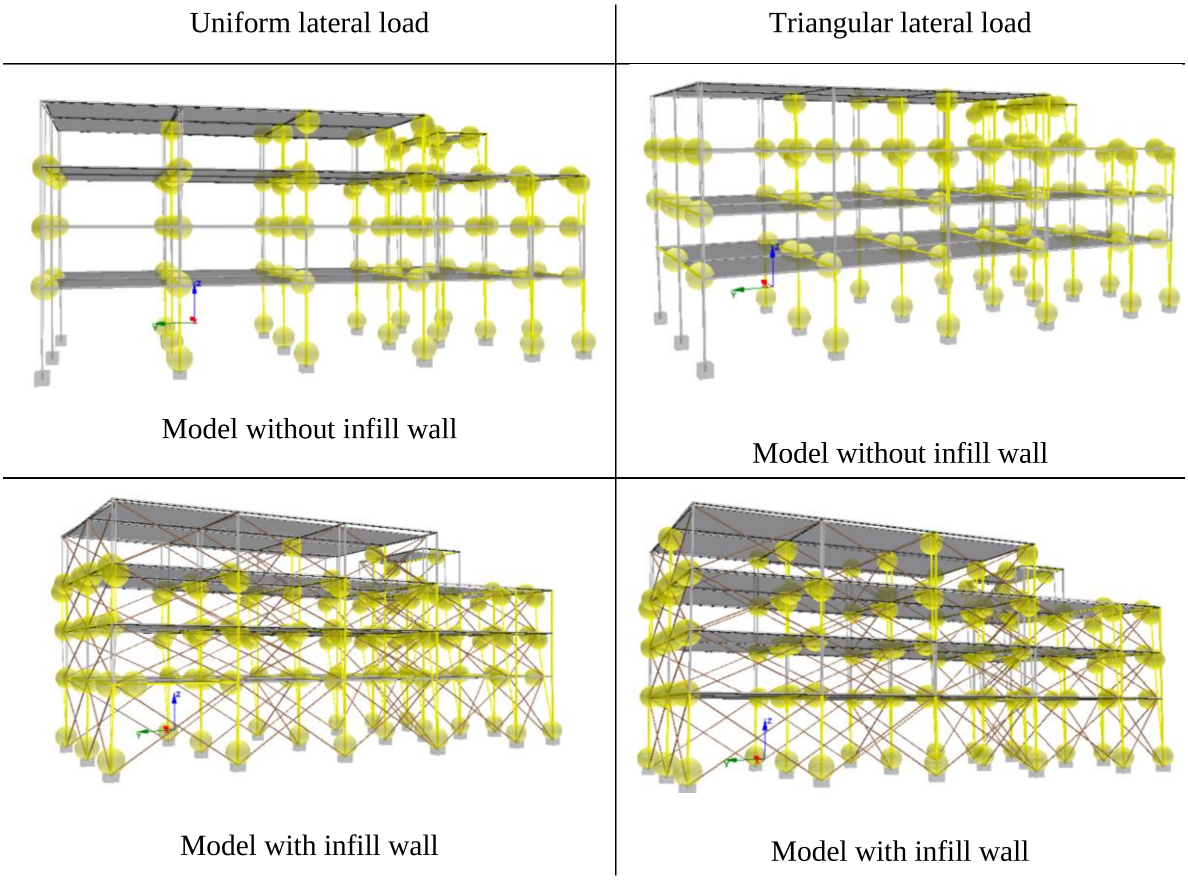


Figure 43 - Plastic hinges for Uniform and triangular lateral load pattern

The capacity curves for the structural model with the infill wall is compared with the capacity curve model without infill wall and is shown in Figure 44.

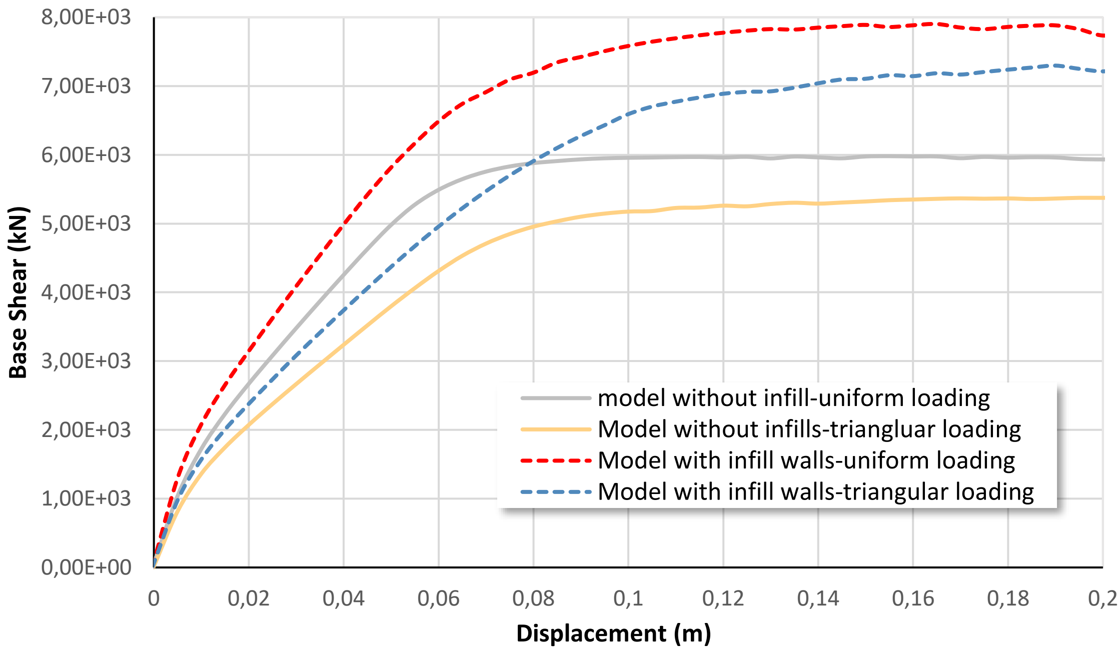


Figure 44 – Capacity curves for building with and without infill walls

The results show that the structure having infill walls considered for the seismic assessment has higher seismic capacity than the structure without infill walls. The ultimate seismic capacity of the case study building with infill walls increases by almost 28% by comparison with the absence of infill walls in the seismic analysis for uniform lateral loading. For triangular lateral loading, the ultimate seismic capacity of the case study building increase by 34% when considered infill walls for the seismic analysis. It was observed that the stiffness of the structure increases with the addition of infill wall. However, the increase in the stiffness of the case study is not so significant than the regular building as shown in Chapter 3. This is due to the reason that the infill walls are not provided in between all the columns in the case study building. Furthermore, the results show that the addition of infill walls doesn't reduce the ductility of the case study building. Overall, the structure is considered as safe for significant damage limitation and hence no strengthening is required.

This dissertation can be considered as the first step for many other BIM uses such as energy conservation, life cycle cost analysis, refurbishment and maintenance etc. to be considered. The current dissertation doesn't focus on the retrofitting techniques but different potential techniques can be applied in the BIM model integrating the building architecture with the structural solution which can be then exported to seismic analysis software.

5. CONCLUSIONS

The main objective of this dissertation was to propose a BIM-based framework to facilitate seismic assessment of existing RC building using non-linear pushover analysis. This framework is strongly based on a visual programming script on the BIM authoring software that enables to query the objects in the model and perform a custom export of data to a specialized software in seismic analysis. The need for this work regards the fact that currently existing frameworks are not able to directly address this specific interoperability particularly in view of the possibility of including infill walls in the process of analysis for added realism of behavioural predictions, and hence more sustainable and cost-effective processes of retrofitting. For the seismic assessment of existing buildings, the EN-1998-3, Eurocode 8 was adopted.

To follow the above objective, a framework was developed in Dynamo which is used to export data from the BIM model (in REVIT) to seismic analysis software (SeismoStruct) for its seismic assessment. A set of modelling rules were established for adequate export and discussed within the dissertation, with a particularly time-effective process to model the reinforcement without the explicit need to model the actual reinforcement bars. The information about reinforcement was rather applied as non-graphical information in the relevant objects (columns and beams), in a way that was sufficient for the data needed for plastic hinge computation in the seismic analysis software. The BIM model was contained all the relevant data for export including geometry, material properties and reinforcement data. Furthermore, to study the effect of infill walls on the seismic capacity of the buildings, the interoperability framework allowed the direct import of the corresponding relevant data from the BIM authoring tool to the seismic analysis software. The framework was developed such that it can export the footings as support conditions for the columns as well. These objectives were achieved and evaluated for two buildings (i). a pilot building previously used in academic exercises; (ii) a building based on a real situation recently studied by Newton, the partner company in this dissertation. The developed framework can export BIM model in XML format which is then imported to Seismic analysis software named SeismoStruct for the seismic analysis.

The following points can be concluded from the studies performed in this dissertation.

- The geometry of all the structural elements including columns and beams are exported from Revit to SeismoStruct. Thus, the added value of having the information available on a BIM model, allows the structural engineer to ease the tasks of modelling/input for the seismic analysis software, thus reducing errors and allowing to concentrate on the highly complex tasks of analyzing results and taking decisions on the potential need for strengthening.

- The material properties for both columns and beams are exported using the framework. The framework is designed such it can export the footing of the columns as well.

- Modelling of reinforcement is one of the complex tasks in the BIM model. The alternative model developed herein, based on a set of non-graphic parameters has revealed itself effective. Time of modelling is strongly reduced as compared to the full modelling of the rebars in the BIM authoring tool. Also, chances of error in modelling are likely to be reduced because of the strong reduction in the necessary operations.

- In this dissertation, the pushover analysis of a typical existing four-storey reinforced concrete building with and without infill walls is performed. The results of the pushover analysis show that the studied structure is sufficient to resist the earthquake loading. Although flexural and shear hinges are developed both in columns and beams at different storeys for both uniform and triangular lateral load pattern, these were developed after the target displacement had been achieved.

- The effect of infill walls on the seismic analysis is often disregarded. It is important to mention the primary originality of the infill wall scenario for a structural design office, which is often seen in research only but can be applied in structural design office with the proposed framework. The studies and research performed in this dissertation show that infill walls have a significant contribution to the seismic capacity of the structure. The seismic capacity of the structure enhances up to 40% when the infill walls are provided continuously both in plan and elevation for the case study building. For the benchmark building, which is regular both in plan and elevations, the effect of infill walls is more substantial, and the base shear of the structure increases up to 100% by considering infill walls. However, when infill walls are considered throughout except the bottom storey, the seismic capacity increases in different proportions for both uniform and triangular loading. For uniform loading the seismic capacity increases by as small as 4% while for triangular loading the seismic capacity was found to increase by 20% compared to no infill wall provided at any storey.

- Overall, the proposed framework has satisfied the initially set requirements of interoperability and demonstrated the feasibility of operation with both case studies presented in Chapters 4 and 5. The necessary information for replication is given throughout the dissertation, both through the process mapping and demonstration, as well as through the information given in the appendices (e.g. source code).

5.1. Future Developments

As future potentially interesting developments in complement to the work done in this dissertation, the following recommendations are suggested.

- The script was initially developed for the pilot building which is a frame structure that contains columns, beams and infill wall and is regular both in plan and elevation. It is important that this script can be further developed to export shear walls which are very frequent in RC buildings. Even though this was not done in the present dissertation (mostly due to time constraints), the necessary methods/code are of similar complexity to those already applied.

- The capacity of the script to use data from actually modelled reinforcement bars in the model (in case the model contains such information) can be an added value if one considers that more and more buildings will start to have such ‘as-built’ information in the future.

- Load application to beams directly in the BIM authoring tool can also be included, through algorithms based on influence-width of loads, and the value of the uniformly distributed dead load. This would reduce the number of tasks for the engineer to conduct in SeismoStruct and maximize the centralization of data in the actual BIM model.

- Even though the present dissertation did not focus in retrofitting techniques, there are several potential techniques that could be applied in the BIM model integrating the structural solution with the building architecture, which could be transferred to the seismic analysis software, allowing to fine-tune the actual reinforcement and retrofit solution regarding actual expected performance.

- In line with the previously mentioned point, it would also be interesting to combine this framework with an optimization algorithm which would allow the engineer to set a space solution for retrofit operations in the BIM authoring tool and let the framework of interoperability explore them through the necessary calculation time, yielding the optimum (at least local optimum) solution at small human labour cost.

This page is intentionally left blank

REFERENCES

1. ISO Standard. (2010) “Building Information Modelling – Information Delivery Manual – Part 1: Methodology and Format”. ISO 29481-1:2010(E)
2. Volk, R.; Stengel, J.; Schultmann, F. (2014): Building Information Models (BIM) for existing buildings –literature review and future needs - Automation in Construction 38, pp.109-127, DOI: 10.1016/j.autcon.2013.10.023.
3. M. Khaddaj, I. Srour, (2016), “Using BIM to Retrofit Existing Buildings”, in: Proc. International Conference on Sustainable Design, Engineering and Construction,Procedia Engineering 145 pp. 1526–1533, Elsevier.
4. Raimar J. Scherer, Peter Katranuschkov, (2018), “BIMification: How to create and use BIM for retrofitting”, Advanced Engineering Informatics 38, pp. 54-66
5. J.J. McArthur, (2015), “A building information management (BIM) framework and supporting case study for existing building operations, maintenance and sustainability” ,Proc. Eng. 118 pp. 1104–1111.
6. Zhen Xu, Xin zheng Lu, Xiang Zeng, Yongjia Xu, Yi Li, (2019), “Seismic loss assessment for buildings with various-LOD BIM data”, Advanced Engineering Informatics, Volume 39, pp. 112-126.
7. R. Volk, J. Stengel, and F. Schultmann, (2014), “Building Information Modelling (BIM) for existing buildings—literature review and future needs,” Automation in Construction, vol. 38, pp. 109–127.
8. U.Vitiello, V.Ciotta A.Salzano, D.Asprone, G.Manfredi, E.Cosenza, (2019), “BIM-based approach for the cost-optimization of seismic retrofit strategies on existing buildings”, Automation in Construction Volume 98, pp. 90-101.
9. M. Oraee, M. R. Hosseini, E. Papadonikolaki, R. Palliyaguru, and M. Arashpour, (2017), “Collaboration in BIM-based construction networks: a bibliometric-qualitative literature review,” International Journal of Project Management, vol. 35, no. 7, pp. 1288–1301.
10. Biagini C., Ottobri P. (2019) Federated Parametric Models for Seismic Risk Analysis in Existing Buildings. In: Cocchiarella L. (eds) ICGG 2018 - Proceedings of the 18th International Conference on Geometry and Graphics. ICGG 2018. Advances in Intelligent Systems and Computing, vol 809. Springer, Cham.
11. David P Welch, Timothy J Sullivan, Andre Filiatrault, (2014) “Potential of Building Information Modelling for Seismic Risk Mitigation in Buildings”.
12. T. Cerovsek, “Advanced Engineering Informatics A review and outlook for a ‘Building Information Model’ (BIM): A multi standpoint framework for technological development,” Advanced Engineering Informatics, vol. 25, no. 2, pp. 224–244, 2011.
13. Maggie Khaddaja, Issam Srour, (2016), “Using BIM to Retrofit Existing Buildings”, International Conference on Sustainable Design, Engineering and Construction, Procedia Engineering 145, 1526 – 1533
14. W. Baran, B. Żymańczyk, (2018), “Structural Engineering by way of BIM”, MATEC Web of Conferences, Vol. 174, https://doi.org/10.1051/matecconf/201817404011

15. Liu, Z. Q., Li, Y. G. and Zhang, H. Y., (2010) "An IFC-based Integration Tool for Supporting Information Exchange from Architectural Model to Structural Model," Journal of Central South University of Technology, Vol. 17, No. 6, pp. 1344-1350. doi: 10.1007/s11771-010-0640-z
16. H.L. Chi, X. Wang, Y. Jiao, (2015), "BIM-Enabled Structural Design: Impacts and Future Developments in Structural Modelling, Analysis and Optimisation Processes", Arch Computat Methods Eng, Vol. 22, pp. 135–151.
17. T. Cerovsek, (2011) "A review and outlook for a building information model (BIM): a multi-standpoint framework for technological development", Adv Eng Inform Vol. 25, pp.224–244.
18. Autodesk Revit for building design and construction. http://www.autodesk.com/products/autodesk-revit-family/overview.
19. Grilo, A.; Jardim-Goncalves, R. 2010. Value proposition on interoperability of BIM and collaborative working environments, Automation in Construction 19(5): 522–530. https://doi.org/10.1016/j.autcon.2009.11.003
20. Wix, J.; Karlshoej, J. (2006) "Information delivery manual guide to components and development methods". buildingSMART International
21. K. Kensek, "Visual Programming for Building Information Modelling", Energy and Shading Analysis Case Studies, Vol.10(4).
22. Costagliola, G., Delucia, A., Orefice, S. and Polese, G. (2002), A Classification Framework to Support the Design of Visual Languages, Journal of Visual Languages and Computing. Vol. 13, pp. 573-600.
23. Zarzycki, A. 2012. "Parametric BIM as a generative design tool," Digital Aptitudes: ACSA Conference, Boston, MA.
24. Makris, M., Gerber, D., Carlson, A., and Noble, D. 2013. "Informing Design through parametric integrated structural simulation: iterative structural feedback for design decision support of complex trusses," eCAADe 2013: Computation and Performance – Proceedings of the 31st International Conference on Education and Research in Computer Aided Architectural Design in Europe, Delft, The Netherlands, September 18-20,2013, ISBN: 978-94-91207-04-4 (vol. 1) · 978-94-91207-05-1 (vol. 2)
25. Agrawal, H., Jain, R., Humar, P., and Yammiyavar, P. 2014. "FabCode: visual programming environment for digital fabrication," IDC '14: Proceedings of the 2014 conference on interaction design and children, pp. 353-356, ACM New York, NY, ISBN: 9781450322720 doi>10.1145/2593968.2610490
26. Briscoe, D. 2014. "Parametric planting: green wall system research + design using BIM," ACADIA 14: Design Agency: Proceedings of the 34th Annual Conference of the Association for Computer Aided Design in Architecture (ACADIA), ISBN 9781926724478, Los Angeles 23-25 October, 2014), pp. 333-338.
27. Eurocode 8, EN-1998-1-3: Assessment and retrofitting of buildings
28. Gülkan, P., and Sözen, M.A., 1974. "Inelastic Responses of Reinforced Concrete Structures to Earthquake Motions", Journal of the American Concrete Institute, v. 71, pp. 604-610.
29. Freeman, S.A., Nicoletti, J.P., and Tyrell, J.V., 1975. "Evaluation of Existing Buildings for Seismic Risk - A Case Study of Puget Sound Naval Shipyard, Bremerton, Washington", Proceedings of the First U.S. National Conference on Earthquake Engineering, Berkeley, CA
30. Saiidi, M., and Sözen, M.A., 1981. "Simple Nonlinear Seismic Analysis of R/C Structures", Journal of the Structural Division, ASCE, Vol. 107, No. ST5, pp. 937-952.

31. Fajfar, P., and Fischinger, M., 1987. "Nonlinear Seismic Analysis of RC Buildings: Implications of a Case Study", European Earthquake Engineering, v. 1, pp. 31-43.
32. Fajfar, P., and Gaspersic, P., 1996. "The N2 Method for the Seismic Damage Analysis of RC Buildings", Earthquake Engineering and Structural Dynamics, v. 25, pp. 31-46.
33. Chopra, A.K., Goel, R.K., 2000. "Evaluation of NSP to Estimate Seismic Deformation: SDF Systems", Journal of Structural Engineering, v.126 (4), pp. 482-490.
34. Krawinkler, H., and Seneviratna, G.D.P.K., 1998. "Pros and Cons of a Pushover Analysis of Seismic Performance Evaluation", Engineering Structures, v. 20, pp. 452-464.
35. Paret, T.F., Sasaki, K., Eilbeck, D.H., and Freeman S.A., 1996. "Approximate Inelastic Procedures to Identify Failure Mechanisms From Higher Mode Effect", 11th World Conference on Earthquake Engineering, Paper No. 966, Acapulco, Mexico.
36. Sasaki, F., Freeman, S., and Paret, T., 1998. "Multi-Mode Pushover Procedure (MMP)-A Method to Identify the Effect of Higher Modes in a Pushover Analysis", Proceedings of the 6th U.S. National Conference on Earthquake Engineering, Seattle, CD-ROM, EERI, Oakland.
37. Chopra, A.K., Goel, R.K., Chintanapakdee, C., 2004. "Evaluation of a Modified MPA Procedure Assuming Higher Modes as Elastic to Estimate Seismic Demands", Earthquake Spectra, v. 20 (3), pp. 757-778.
38. Kalkan, E., and Kunnath, S.K., 2006. "Adaptive Modal Combination Procedure For Nonlinear Static Analysis of Building Structures", ASCE, Journal of Structural Engineering, v. 132 (11), pp. 1721-1731.
39. Fajfar, P., EERI, M., (2000)," A nonlinear analysis method for the performance-based seismic design", Earthquake Spectra, Vol. 16, No.3, pp. 573-592.
40. W. F. Chen, (1982), "Plasticity in Reinforced Concrete", New York: J. Ross Publishing.
41. Giannopoulos, P.I. (2009) Seismic Assessment of RC Building According to FEMA 356 and Eurocode 8. *Proceedings of the* 16*th Conference on Concrete*, TEE, ETEK, 21-23 October 2009.
42. Vijayakumar, D.L. (2012) Pushover Analysis of Existing Reinforced Concrete Framed Structures. *European Journal of Scientific Research*, 71, 195-202.
43. Jitendra, N., Balaji, K.V. and Gopalaraju. S.S.V. (2012) Pushover Analysis of Unsymmetrical Framed Structures on Sloping Ground. *International Journal of Civil, Structural, Environmental and Infrastructure Engineering Research and Development* (*IJCSEIERD*), 2, 45-54.
44. Krawinkler, H. and Seneviratna G. D. P. K., (1998), "Pros and Cons of a Pushover Analysis of Seismic Performance Evaluation", J. of Engineering Structures.
45. G. Lee, R. Sacks, and C. M. Eastman, (2006) "Specifying parametric building object behavior (BOB) for a building information modelling system," vol. 15, pp. 758–776.
46. Bazilevs Y, Calo .VM, et al. (2010), "Isogeometric analysis using T-splines", Computer Methods in Applied Mechanics and Engineering Volume 199, Issues 5–8, 1 January 2010, Pages 229-263.
47. Succar. B, (2009), "Building information modelling framework: A research and delivery foundation for industry stakeholders", Automation in Construction Volume 18, Issue 3, May 2009, Pages 357-375

48. H. Penttila, M. Rajala, S. Freese, (2007), Building information modelling of modern historic buildings, Predicting the Future, 25th eCAADe Konferansı, Frankfurt Am Main, Germany, 607–614.
49. F. Fedorik and T. Makkonen and R. Heikkilä, (2016), Integration of BIM and FEA in Automation of Building and Bridge Engineering Design, 33rd International Symposium on Automation and Robotics in Construction
50. Mehdi Alirezaeia, Mehdi Noorib, Omer Tataric*, Kevin R Mackied, Ahmed Elgamal (2016), "BIM-Based Damage Estimation of Buildings under Earthquake Loading Condition", International Conference on Sustainable Design, Engineering and Construction.
51. Carmen Angulo, Karen. Díaz, José M. Gutiérrez, Andrea Prado, Rosanna Casadey, Gino Pannillo, Felipe Muñoz-La Rivera, Rodrigo F. Herrera, Juan C. Vielma (2020), "Using BIM for the Assessment of the Seismic Performance of Educational Buildings", International Journal of Safety and Security Engineering, Vol. 10, No. 1, pp. 77-82
52. Cátia Raposo, Fernanda Rodrigues, Hugo Rodrigues (2019), "BIM-based LCA assessment of seismic strengthening solutions for reinforced concrete precast industrial buildings" Innovative Infrastructure Solutions 4:51.
53. Rúben Santosa, António Aguiar Costa, José D. Silvestre, Lincy Pyl (2019) "Integration of LCA and LCC analysis within a BIM-based environment" Automation in Construction, Vol. 103, pp. 127-149.
54. Santos R et al (2019) Integration of LCA and LCC analysis within a BIM-based environment. Autom Constr 103(February):127–149. https://doi.org/10.1016/j.autcon.2019.02.011
55. European Commission Buildings [2018]; Available from https://ec.europa.eu/energy/en/topics/energy-efficiency/buildings
56. J. Zuo, S. Pullen, R. Rameezdeen, H. Bennetts, Y. Wang, G. Mao, Z. Zhou, H. Du, H. Duan, Green building evaluation from a life-cycle perspective in Australia: a critical review, Renew. Sust. Energ. Rev. 70 (2017) 358–368, https://doi.org/10. 1016/j.rser.2016.11.251.
57. J. Díaz, Á. Antön Laura, Sustainable construction approach through integration of LCA and BIM tools, Computing in Civil and Building Engineering, 2014, https://doi. org/10.1061/9780784413616.036.
58. Sharareh Kermanshachi, and Behzad Rouhanizadeh, (2018), "Feasibility Analysis of Post Disaster Reconstruction Alternatives Using Automated BIM-Based Construction Cost Estimation Tool", Building Tomorrow's Society.
59. Symeon E. Christodoulou, Dimitrios Vamvatsikos, Costas Georgiou, (2010), "A BIM-based framework for forecasting and visualizing seismic damage, cost and time to repair", eWork and eBusiness in Architecture, Engineering and Construction, pp. 33-38
60. Azhar, S., Hein, M., Sketo, B. (2008) "Building Information Modelling (BIM): Benefits, Risks, Challenges". Associated Schools of Construction (ASC) 44th Annual Conference. Auburn, Alabama
61. Eastman, C., Teicholz, P., Sacks, R., Liston, K. (2011) BIM Handbook: A guide to building information modelling for owners, managers, designers, engineers and contractors – 2nd Edition. Wiley, Hoboken, New Jersey.
62. Zhang, J.P., Hu, Z.Z. (2011) "BIM- and 4D-based integrated solution of analysis and management for conflicts and structural safety problems during construction: I. Principles and methodologies". Automation in Construction 20 (2): 155-166.

63. Domaneschi, M.; Villa, V.; Cimellaro, G. P.; Caldera, C.; Zamani Noori, A.; Marasco, S.; Ansari, F, (2019), “Integrating BIM with onsite investigation for seismic vulnerability assessment”, 7th International Conference on Computational Methods in Structural Dynamics and Earthquake Engineering, pp. 544-553.
64. Zhen Xu, Huazhen Zhang, Xinzheng Lu, Yongjia Xu, Zongcai Zhang, Yi Li, (2019), “A prediction method of building seismic loss based on BIM and FEMA P-58” Automation in Construction. Vol 102, pp. 245-257.
65. Aldegeily, M., Yufeng Hu, Xiaoyun Shao, Jiansong Zhang, (2018), “From Architectural Design to Structural Analysis: A Data-Driven Approach to Study Building Information Modelling (BIM) Interoperability” 54th ASC Annual International Conference Proceedings.
66. Qin, L.; Deng, X.-y.; Liu, X.-l. (2011), “[”, Journal of Shanghai Jiaotong University (Science) Vol. 16(1), pp. 83–90.
67. Kim, Y.-W.; Azari-N, R.; Yi, J.-S.; Bae, J. (2013), “Environmental impacts comparison between on-site vs. prefabricated Just-In-Time (prefab-JIT) rebar supply in construction projects”, Journal of Civil Engineering and Management Vol. 19(5): pp. 647–655.
68. Venugopal, M.; Eastman, C. M.; Sacks, R.; Teizer, J. (2012), “Semantics of model views for information exchanges using the industry foundation class schema”, Advanced Engineering Informatics Vol. 26(2): pp. 411–428.
69. Marina Figueiredo Muller, Amanda Garbers, Filipe Esmanioto, Natan Huber, Eduardo Rocha Loures & Osiris Canciglieri Junior (2017), “Data interoperability assessment through IFC for BIM in structural design – a five-year gap analysis”, Journal of Civil Engineering and Management, Vol. 23(7), pp. 943-954,

APPENDIX 1: DYNAMO SCRIPT

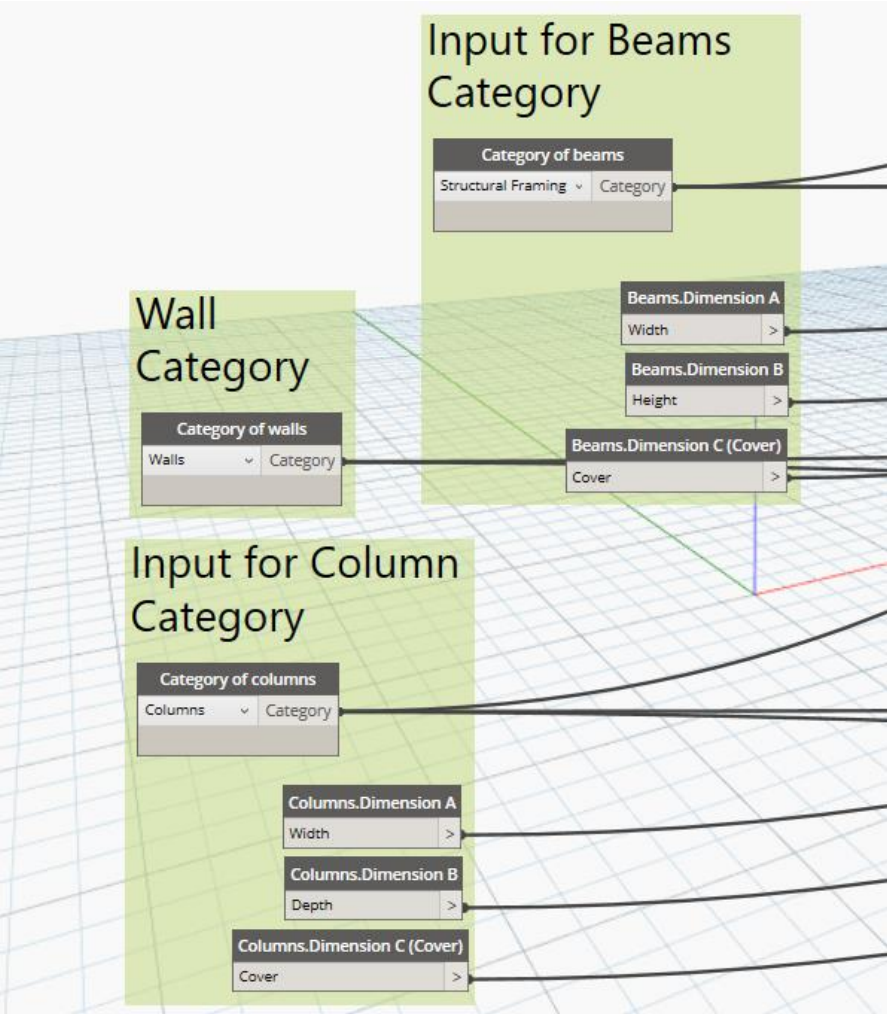
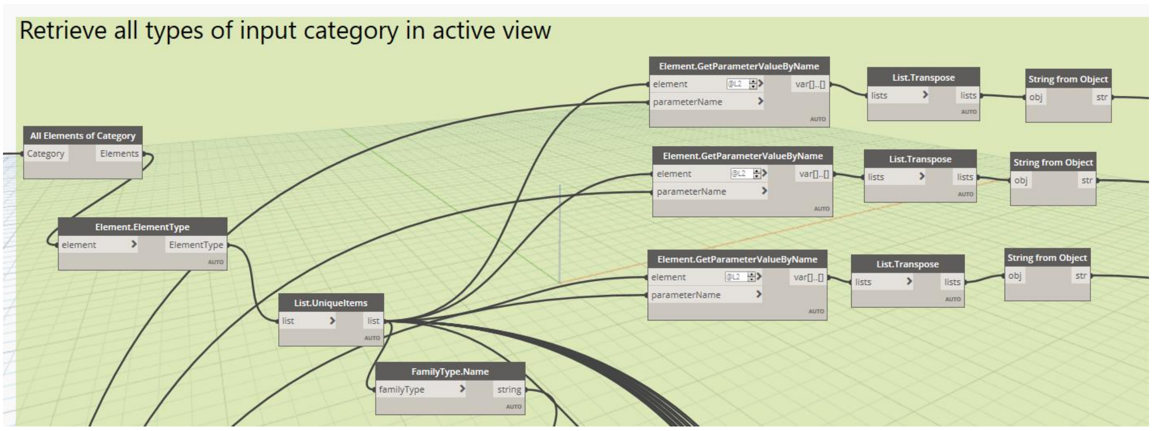


Figure 1-1 Defining input category



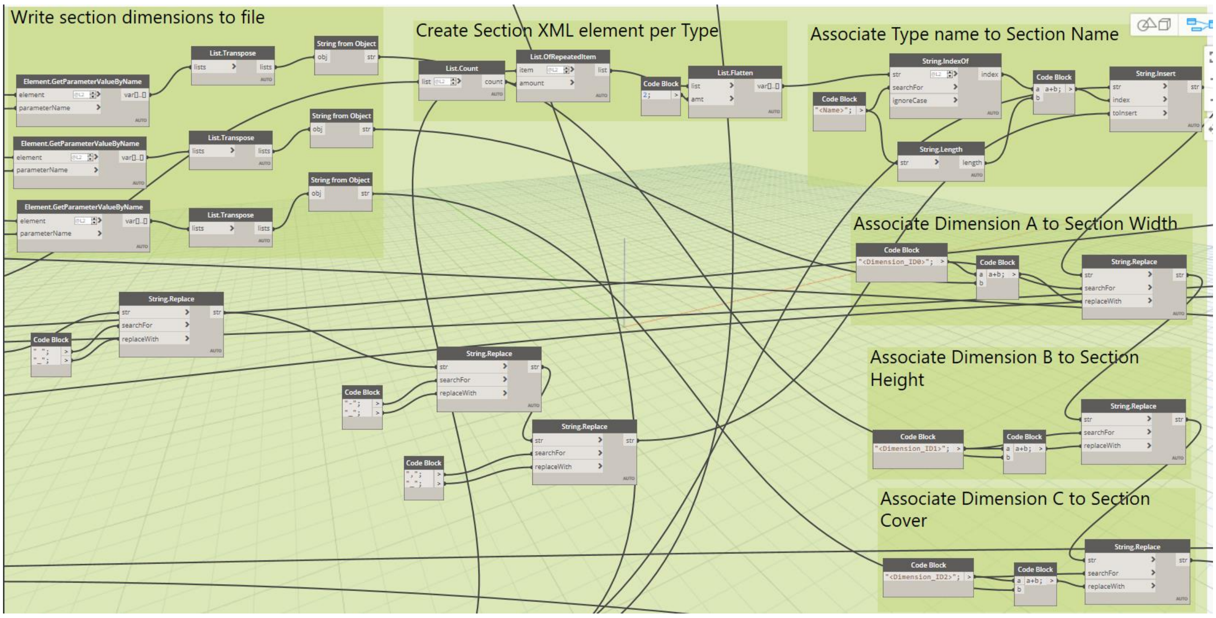


Figure 1-2 Retrieving input category and associating type name to section

Figure 1-3 Extraction of reinforcement parameters

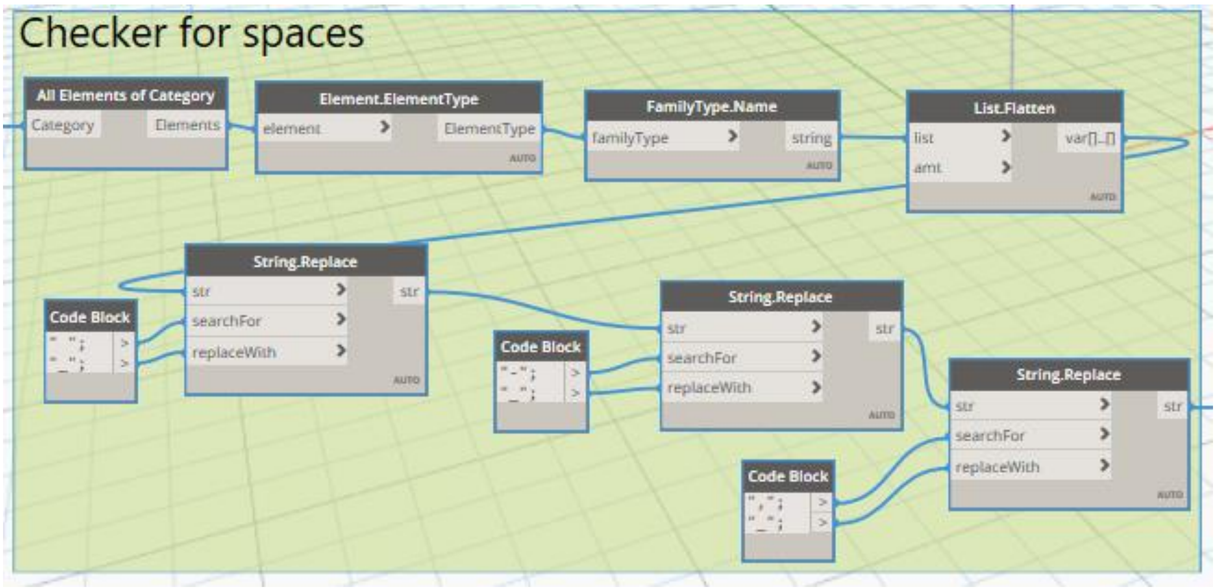


Figure 1-4 spacing check and replace with hyphen

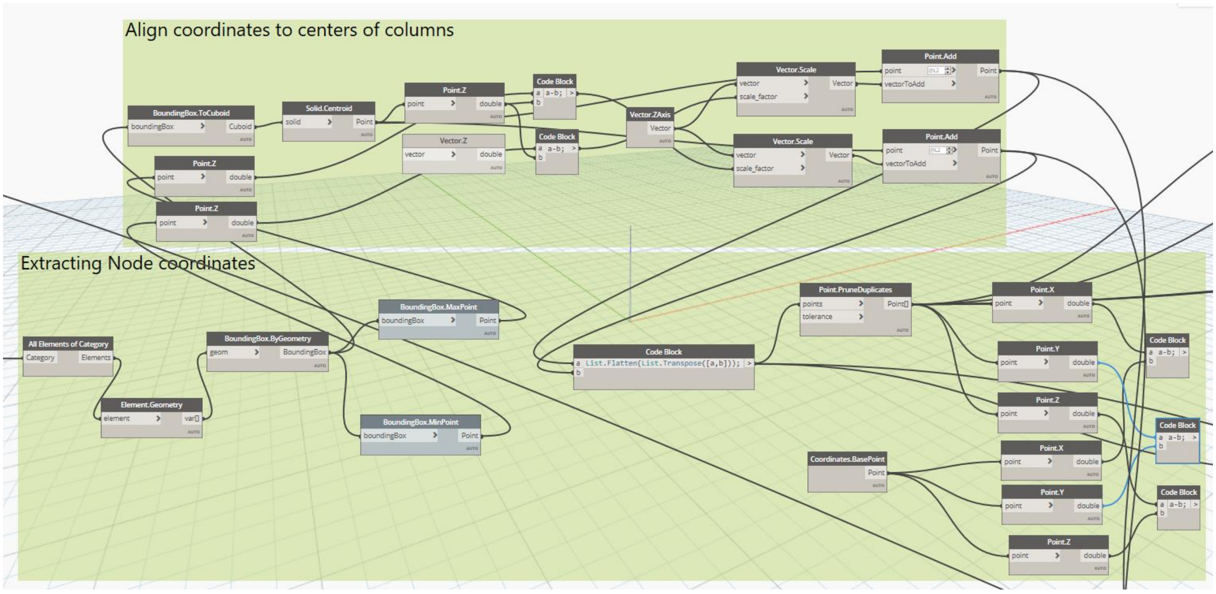


Figure 1-5 Extraction of node coordinates and aligning it to centre of columns

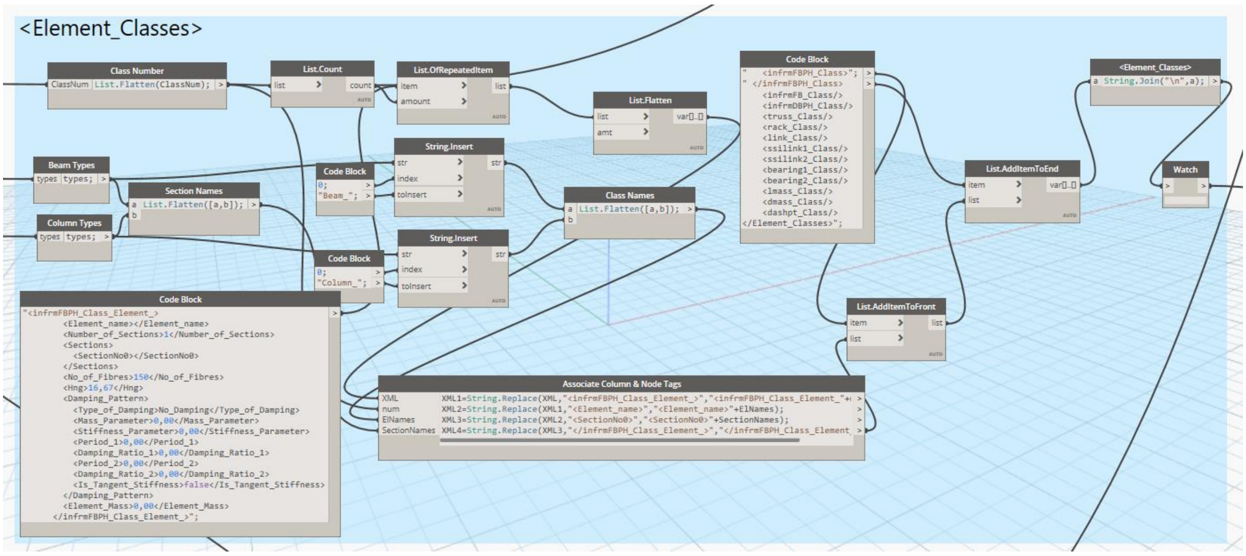


Figure 1-6 Defining element classes

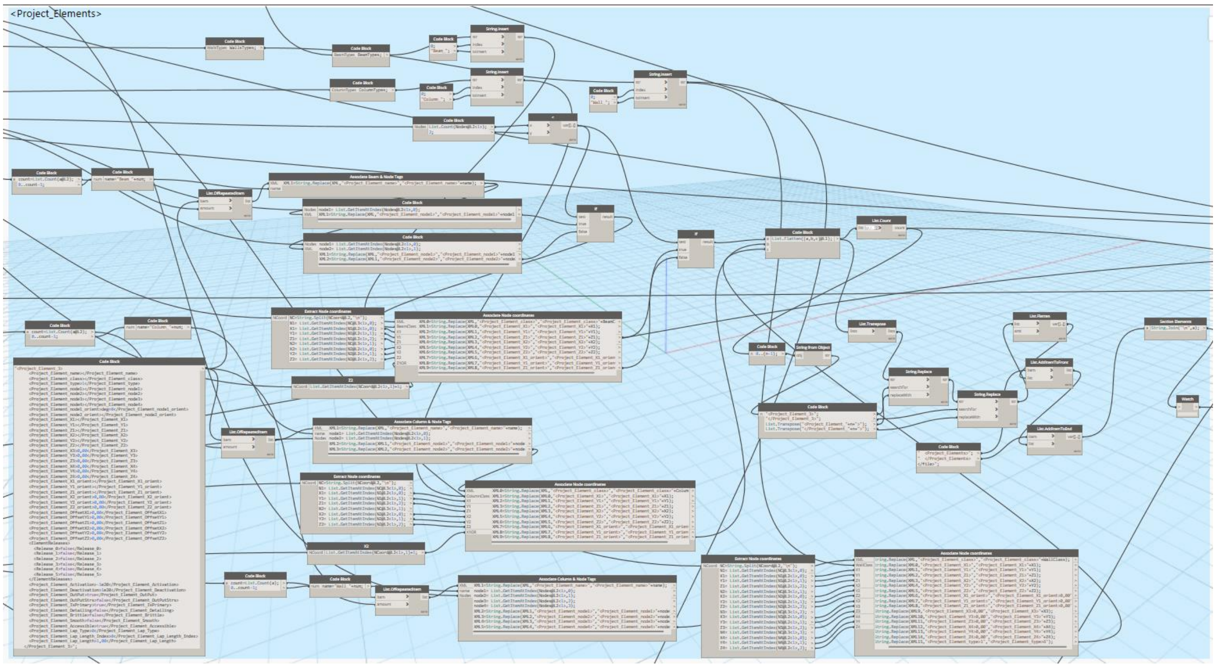


Figure 1-7 Defining project elements

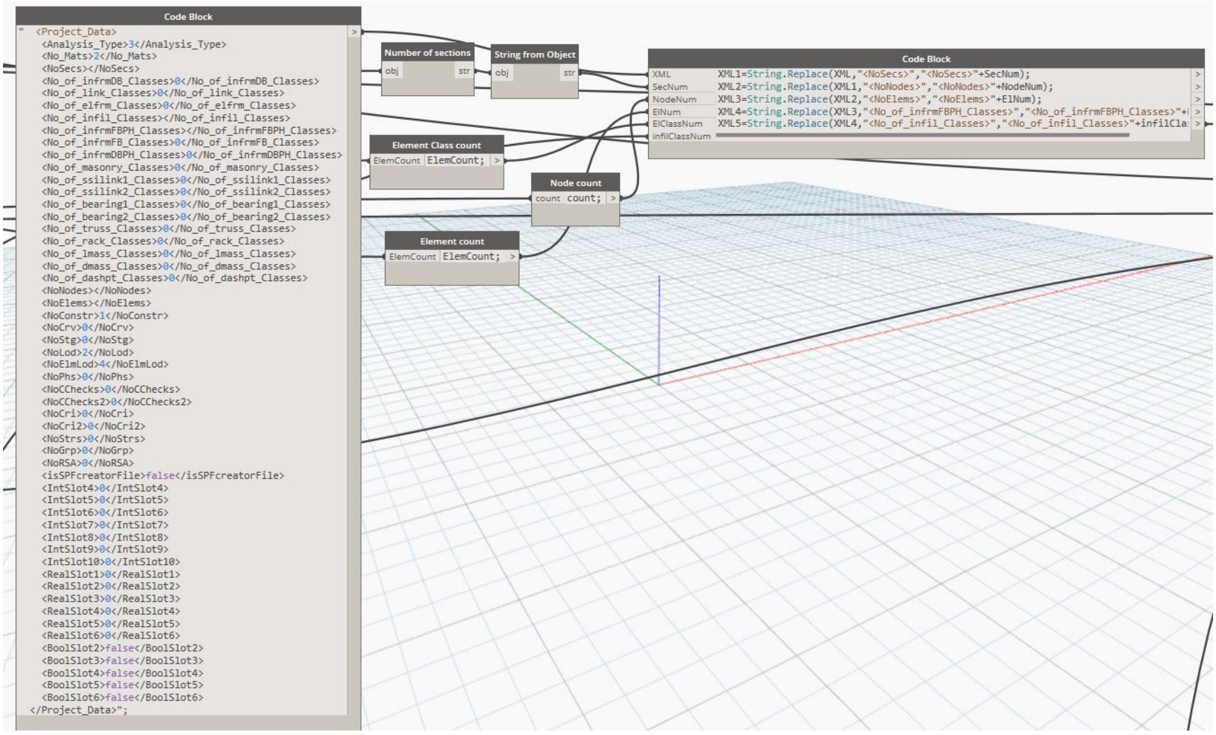


Figure 1-8 Integration of the whole framework

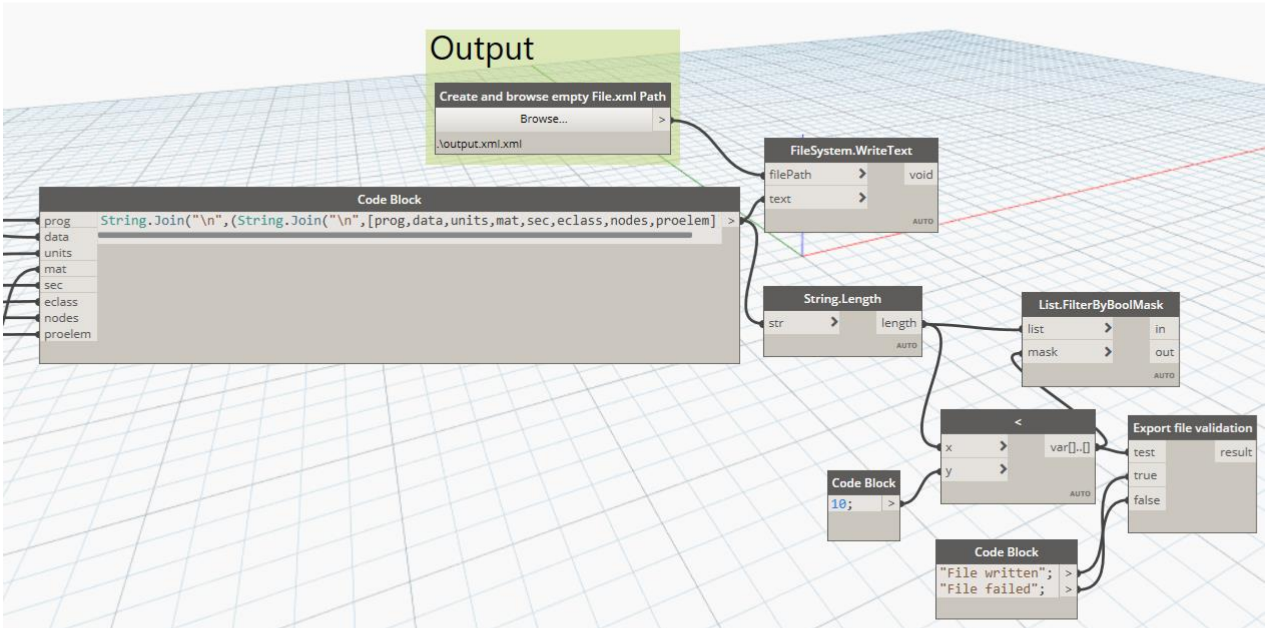


Figure 1-8 Defining file path for exporting to XML format\

APPENDIX II: USER MANUAL FOR THE TOOL

This manual is prepared for the user who wants to use the script for the interoperability between Autodesk Revit and SeismoStruct. For this purpose, a single-storey frame structure has been modelled according to the guidelines stated above to assist future users.

Units

The units shown in Table 14. are required to be used for the interoperability:

Table 14 – Units to be used

Units description	
Length, width, depth, thickness, spacing, concrete cover	Meter (m)
Stresses and strength	kPa
Mass	tonne
Acceleration	m/sec2
Force	kN
Reinforcement (bar) diameter	mm

Step 1. Structural details:

Let's we have a frame structure having 2 columns, a beam and an infill wall. The geometry and material properties of these structural members are presented in Table 15 and Table 16 respectively.

Table 15 – Geometry of structural elements

Column 1.	
Size	400*500 (mm2)
Column 2.	
Size	300*500 (mm2)
Beam.	
Size	300*500 (mm2)

Table 16 – Material properties of structural elements

Materials	
Steel yield strength	440 MPa
Concrete compressive strength	22 MPa
Concrete cover	15 mm

The geometry and reinforcement provided in these structural elements are shown in Table 17. The plan view of this frame is illustrated in Figure 45.

Table 17 – Reinforcement information

Column-1	Column-2	Beam
0.40*0.5 **LR: 8ø16** **TR: ø6/0.20m**	0.30*0.5 LR: 6ø16 TR: ø6/0.2m	0.30*0.50 LR: 8ø12 TR: ø6/0.20m

LR: Longitudinal reinforcement, TR: Transverse reinforcement

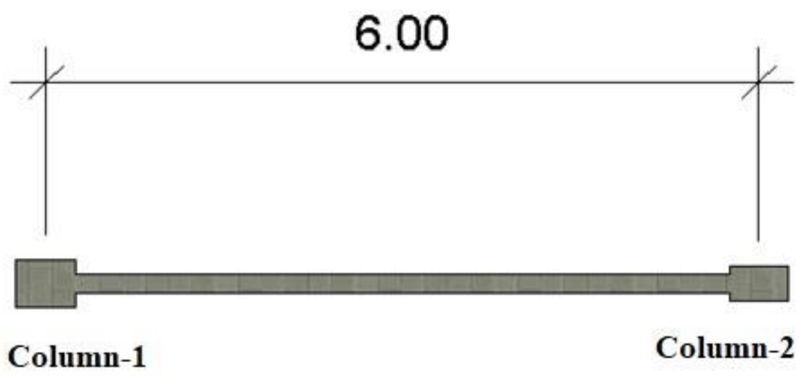


Figure 45 – Plan view of the structure

The material and geometrical properties of the infill wall are shown in Table 18.

Table 18 – Material properties and characteristics of infill wall

Thickness	**50 mm**
Compressive strength	660 kPa
Tensile strength	100 kPa
Young's modulus	1837000 kPa

Shear bond strength	20 kPa
Specific weight	5.8 kN/m3
Maximum shear resistance	40 kPa

Step 2. Model the structure in Revit

The structure is modelled in Revit as shown in Figure 46. All the material and geometrical properties need to attach to the structural elements as Type Parameter as shown in Figure 47.

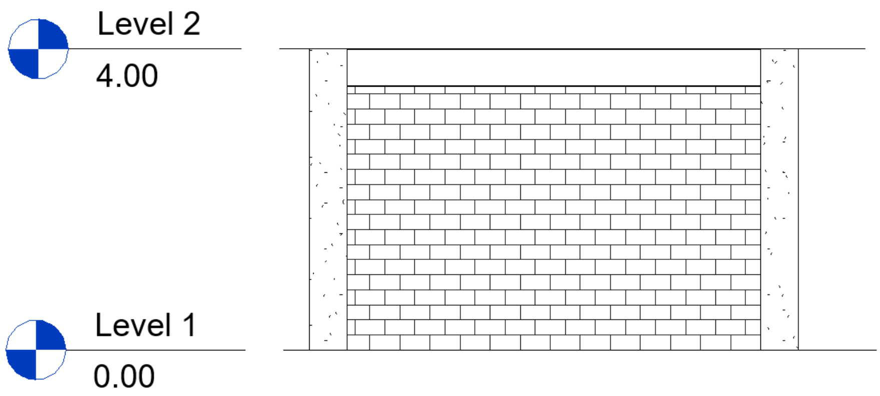


Figure 46 – Modelled frame in Revit

Dimensions	
Cover	0.0250
Depth	0.5000
Offset Base	0.0000
Offset Top	0.0000
Width	0.4000

Identity Data	
Concrete-strength	22000
yield-strength	440000

Figure 47 – Geometrical and material properties for Column 1

Reinforcement data:

The reinforcement information needs to be provided as a type parameter to all the columns and beams and should be in the following format.

- The main/longitudinal reinforcements in both beams and columns are represented as upper-bar, lower-bar and side-bar as shown in Figure 48 (Left).
- The transverse reinforcement is represented by the number of shear legs in each direction of the structural member. Figure 48 (Right) highlights the shear legs along the width. In this case, there are 4 shear legs along with width and 2 shear legs along with the height of the member.

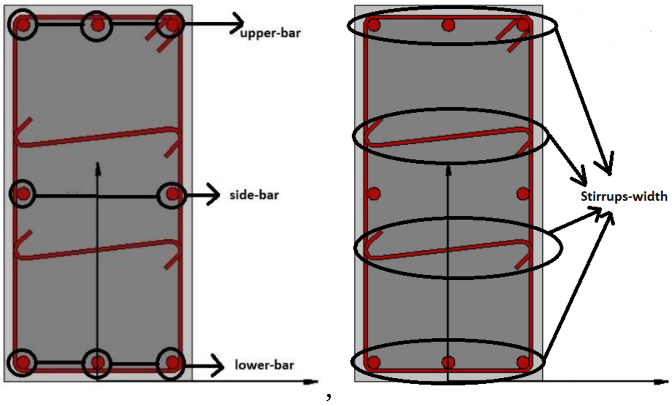


Figure 48 – Longitudinal reinforcement and transverse reinforcement

For the reinforcement shown in Figure 48, the information is presented and attached to the structural elements in Revit as shown in Figure 49.

Structural	
lower-bar	3
lower-bar-dia	16
upper-bar	3
upper-bar-dia	16
side-bar	2
side-bar-dia	16
stirrup-width	4
stirrup-height	2
stirrup-dia	6
stirrup-spacing	0.200000

Figure 49 – Reinforcement information attached as a Type parameter

Infill wall:

The geometrical and mechanical properties of the infill wall are also attached as Type parameter as shown in Figure 50.

Structural	
wall-thickness	0.050000
compressive-strength	660.000000
specific-weight	5.800000
tensile-strength	100.000000
young-modulus	1837000.000000
shear-bond-strength	200.000000
max-shear-resistance	400.000000

Figure 50 – Infill wall

Running the script

After modelling the structures, and attach all the required metadata as stated above, the script is ready to execute. In order to run the script using Dynamo Player, it is required to save the dynamo file in the location as shown in Figure 51.

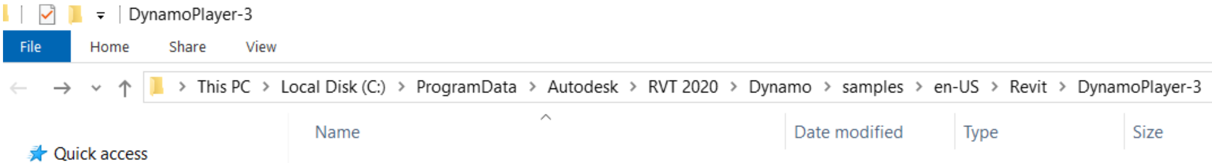


Figure 51 – Location/Path for saving the dynamo script

Furthermore, the same copy of the dynamo script needs to be saved in a folder at the desired location in the Hard drive. In addition, an empty XML file needs to be saved in the folder containing the dynamo file. Lastly, Open the Dynamo Player in Revit, click on Run as shown in Figure 52, and the XML file will be generated and will replace the empty XML file.

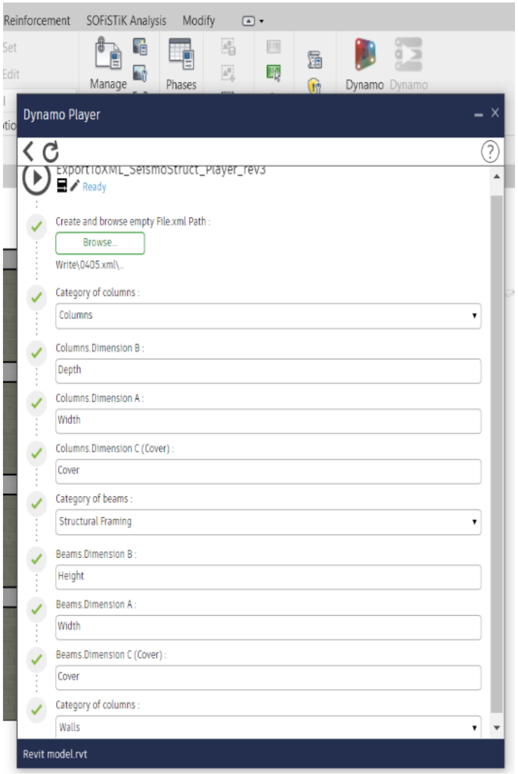


Figure 52 – Run the script using Dynamo Player

Import the XML file

Finally, the XML file which is generated is import to SeismoStruct for Seismic Assessment as shown in Figure 53. After importing the file, the seismic assessment can be performed.

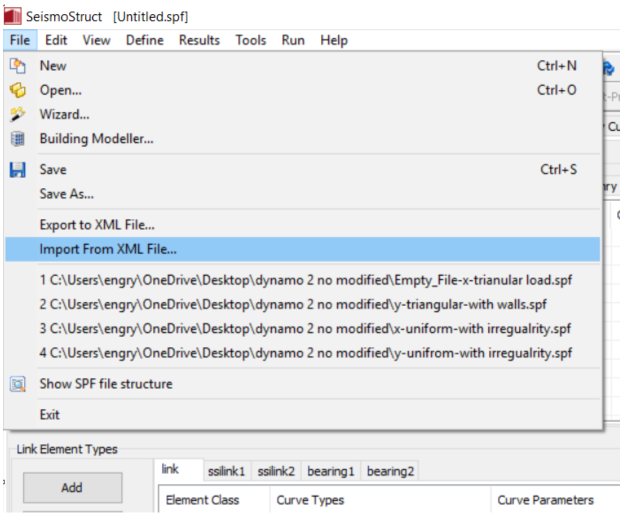


Figure 53 – Import XML file