SYNTHETIC RATING SYSTEM FOR RAILWAY BRIDGE MANAGEMENT

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Abstract

Railway bridges deteriorate over time due to different critical factors including live load, fatigue, extreme events (e.g. flood, wind, and earthquake), collision, and many environment factors (e.g. corrosion, wear, and termite attack). One of the most important parts of any Bridge Management System (BMS) is the condition assessment and rating of bridges. As there are thousands of bridges and several factors that cause deterioration, the rating process is extremely complicated. Current simplified but practical rating methods that can be applied to a network of bridges are not based on a reliable structural condition assessment system and are very subjective. On the other hand, sophisticated, but more reliable methods are only used for a single bridge. It is therefore necessary to develop a practical and accurate system, capable of rating a network of railway bridges for management purposes.

This research develops a new synthetic method for rating a network of railway bridges based on their current and future structural conditions. The current condition of a bridge shows whether the structure is safely serviceable at the time of inspection. The future condition of a bridge should also be anticipated through appropriate methods to determine the rate of bridge deterioration. Rating bridges based on their current and future conditions is used to identify the best time for intervention.

The proposed method developed new rating equations. In these equations, the importance of critical factors and weighting factors associated with different components of the bridge were taken into account. The importance of critical factors shows the contribution of different critical factors towards bridge deterioration, and they were quantified using a new method in this research. Using this method, the risk assessments conducted in different design standards associated with different critical factors were adopted. The Analytic Hierarchy Process (AHP) was used to synthesise the priorities and calculate the overall priorities of the critical factors. It was also used to incorporate the experts' opinion for decision-making.

The weighting factors showing the criticality and vulnerability of the components at the time of conducting structural analysis were calculated based on the method developed in this research. Using this method, structural analyses were mainly used to calculate the weighting factors of components associated with different critical factors. Based on the condition of the components at the time of inspection, the importance of critical factors, the weighting factors, and the proposed rating equations, the ratings of the bridge and its components in the network were calculated. The synthetic rating method developed is illustrated by application to two bridges. This research also investigated the effect of resonant vibration on the weighing factors associated with train load. The importance of the safety and serviceability of the bridge to train load was the reason for this investigation.

For the first time, the proposed method incorporates structural analysis, available knowledge of risk assessment in structural engineering standards, and the experience of structural engineers in a practical way to enhance the reliability of the condition assessment and rating bridges in a network. Efficient usage of resources and enhancing the safety and serviceability of railway bridges will be the significant outcomes of using this rating method.

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List of Abbreviations

ACR	Average Condition Rating
AGR	Average Group Rating
AHP	Analytic Hierarchy Process
ANN	Artificial Neural Network
ARI	Average Return Interval
BCCR	Bridge Current Condition and Rating
BCN	Bridge Condition Number
BCR	Bridge Condition Rating
BFCR	Bridge Future Condition and Rating
BMS	Bridge Management System
BOCR	Bridge Overall Condition and Rating
BVRCo	Bridge Vulnerability and Rating to Collision
BVREn	Bridge Vulnerability and Rating to Environment
BVREq	Bridge Vulnerability and Rating to Earthquake
BVRFl	Bridge Vulnerability and Rating to Flood
BVRWd	Bridge Vulnerability and Rating to Wind
CCRLL	Component Criticality and Rating to Live Load
CER	Critical Element Rating
CInsp	Condition of component based on Inspection
CMav	Condition of component based on Markov Chain
CR	Consistency Ratio, and Criticality Rating
CVRCo	Component Vulnerability and Rating to Collision
CVREn	Component Vulnerability and Rating to Environment
CVREq	Component Vulnerability and Rating to Earthquake
CVRFl	Component Vulnerability and Rating to Flood
CVRWd	Component Vulnerability and Rating to Wind
D/C	Demand by Capacity ratio
DAF	Dynamic Amplifications Factor
FCM	Fracture Critical Members

FRP	Fiber-Reinforced Polymer
HHT	Hilber-Hughes-Taylor
LC	Lost Capacity
LCMRB	Life Cycle Management of Railway Bridges
LRFD	Load and Resistance Factor Design
LRFR	Load and Resistance Factor Rating
MADM	Multi Attributive Decision Making Model
MPN	Maintenance Priority Number
NCC	New Component Condition
NDT	Non-Destructive Testing
NWF	New Weighting Factors
R&M	Repair and Maintenance
RCI	Random Consistency Index
SHM	Structural Heath Monitoring
SLS	Serviceability Limit State
SPM	Structural Performance Monitoring
SR	Sufficiency Rating
SRP	Synthetic Rating Procedures
SSE	Structural Safety Evaluation
ULS	Ultimate Limit State
WPM	Weighted Product Model
WSM	Weighted Sum Model

Statement of Original Authorship

The work contained in this thesis has not been previously submitted to meet requirements for an award at this or any other higher education institution. To the best of my knowledge and belief, the thesis contains no material previously published or written by another person except where due reference is made.

QUT Verified Signature

Signature:

Date: 9th February 2015

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Chapter 1: Introduction

This chapter outlines the background (Section 1.1) of the study, the overarching objectives of the study (Section 1.2) and an outline of the remaining chapters of the thesis (Section 1.3).

1.1 BACKGROUND

Railway bridges are vital elements in railway networks, designed to be serviceable for a long time. The collapse of some rail and road bridges provides evidence of problems with current inspection procedures and in the condition assessment of Bridge Management Systems (BMSs) (Belfast Telegraph, 2010). To enable railway bridges to be safe and functional, timely action for maintenance, repair or rehabilitation is essential. As there are thousands of railway bridges at the network level, with restricted resources, it is necessary to develop a more cost effective BMS compared to the existing BMSs. Through a sound BMS, managers and engineers can manage the life-cycle costs of bridges, which increase as they become older and more heavily used. One of the most important tasks of every BMS is to provide a cost effective plan to prioritise bridges for maintenance and repair actions.

Prioritization of bridges and their components for repair and maintenance is based on the risk associated with the probability and the consequences of failure. In order to estimate the probability of the failure of railway bridges, and identify those which are in most need of repair and maintenance, engineers should assess the current condition of the bridges and predict their future condition. The consequences of failure at bridge and network levels are presented in terms of cost and are taken into account in the project ‘Life Cycle Management of Railway Bridges’ (LCMRB). This research made up one of the three main parts of the LCMRB.

The LCMRB aimed at minimizing the cost in order to provide an adequate level of safety for railway bridges during their lifetime. The three important sections of LCMRB include 1) the development of a synthetic rating system for a network of railway bridges (this research), 2) prediction of the remaining service potential of railway bridges, and 3) the development of an optimal life time strategy for repair and maintenance of railway bridges at the network level. In brief, introducing different strategies for maintenance, appropriate time for intervention through consistent inspection and rating systems, and estimating the remaining service life of bridges were the main objectives of this LCMRB project.

This thesis, as a part of the LCMRB, focused on the rating of railway bridges where only the structural factors were taken into account. Other factors such as non-structural factors, remaining service potential and maintenance strategies were considered at the preceding two other sections of the LCMRB. Through the proposed rating method in this thesis, the most vulnerable bridges and their components in a network of railway bridges based on their current condition were identified. In addition, the most vulnerable bridges in a network based on the future condition of their components and the importance of the bridge components for the load carrying capacity of each bridge in a network were identified. Some of the publications arising from this research and LCMRB are mentioned in the reference list of this thesis (Aflatooni et al., 2012b; Nielsen et al., 2013a, 2013b; Wellalage et al., 2013; Aflatooni et al., 2014; Wellalage et al., 2014; Aflatooni et al., 2015).

Rating bridges currently starts with the inspection. Through inspection, inspectors provide data on the condition of a bridge. Engineers conduct the condition assessment of the railway bridges based on the data provided through the inspection process. As inspection processes can be very costly, different inspection levels are defined in BMS, from the most economical to the most expensive, depending on the type of defect, criticality of the situation and vulnerability of the structure. The first level is a visual inspection and consumes the least resources and requires the least expertise. Higher levels, such as the in-depth inspection, require more equipment, resources, and knowledge. As the most important factor in any BMS is cost, visual inspection is popular, and is carried out more frequently than others. The higher levels, which are more reliable, are conducted when defects cannot be detected through lower levels of inspection.

Finding the balance point for intervention, where the ratio of the cost for repair to increase the remaining service life of the bridge is minimum, and selecting the best rehabilitation method, is highly dependent on the type of information needed from an inspection process. A review of the literature highlights that the quality and the quantity of data currently gathered through inspection processes is insufficient and unsatisfactory. This data does not provide adequate information to engineers on the current condition of the railway bridges and does not contain sufficient information to predict their future condition. In addition, in current inspection processes, it is not clear when more costly methods have to be used.

The next part of condition assessment is analysing the data obtained from inspection processes for each individual element of a bridge to identify their effects on the integrity of the structure and evaluate the condition of the bridge. There are different structural methods for this purpose, and some require less experience, knowledge and equipment, such as approximate methods for analysing the structure. However, the results are not very reliable. For practicality reasons, subjective methods are used in current practice to deal with condition assessment and rating of railway bridges at the network level. In these methods, unreliable weighting factors are used. In fact, making a method more practical or simple to use significantly decreases the reliability of subjective methods. Moreover, the practicality is still not sufficiently satisfactory, as subjective methods are not fully applied. In these methods, the role of each component of the bridge on the integrity of the whole structure is not properly taken into account. In addition, the vulnerability of the structure and its components to each critical factor is not determined.

On the other hand, there are methods for the condition assessment of important or complex bridges with a higher level of redundancy. In these methods, the criticality and vulnerability of the structure to some critical factors are taken into account. These methods are more costly, as more complex structural analyses including analyses for identifying the sequence of collapses are conducted. In addition, more costly methods for inspection and condition monitoring of the bridge are used. Although these methods are more reliable, their usage is limited to important bridges individually, as they need much more expertise and resources and they consume much more time. Therefore, these methods cannot be widely used for a network of thousands of railway bridges.

Based on the shortcomings of the current rating methods this research focussed on answering the following key question in order to develop a more reliable rating method than current existing rating systems:

- How can a reliable and practical rating method be developed to remove the sources of subjectivity of current existing rating systems?

To answer the above key question a number of sub-questions were required, as follows:

- What are the critical factors that contribute to the deterioration of the condition of a network of railway bridges, and how they can be quantified in a reliable way?
- How can the importance of a component of a bridge be evaluated in a reliable way when the bridge is subjected to different loads?
- What recommendations are suggested for current inspection processes to collect more sufficient and relevant data about the condition of bridges?

1.2 AIM AND OBJECTIVES

To overcome the shortcomings identified in the review of literature and to address the above research questions, this research developed a sound rating method, considered to be practical and sufficiently reliable to be applied to a network of railway bridges. In order to be useful for life cycle bridge management, the method took into account the current and future conditions of a network of railway bridges. To achieve development of such a rating method, the objectives were as follows:

- Identify the critical factors which contribute towards bridge deterioration and quantify their contributions;
- Determine the criticality and vulnerability of the components of each bridge in a network of railway bridges associated with each critical factor;
- Estimate the vulnerability of each railway bridge in a network of railway bridges associated with different critical factors;
- Provide recommendations for obtaining relevant and sufficient data through inspection processes.

The proposed rating system should therefore have the following characteristics:

1- Sophisticated enough (by using the concept of criticality and vulnerability methods) to be capable of taking into account more critical factors and assessing the condition of railway bridges more accurately.

2- Simple and practical (by using the concept of the subjective methods based on assigning weighting factors to the components of a bridge) with understandable logic for the user who applies the method for condition assessment and rating bridges.

3- Economical.

To achieve the objectives of this thesis, the critical factors that contribute to bridge deterioration were first identified and then placed under different categories, based on the manner in which they caused degradation of the structure, in order to obtain the most reliable method of quantifying them. The effect of each critical factor on a structure was investigated, and the method for calculating the criticality of the components while they were subjected to train loads was identified. In addition, the method for evaluating the vulnerability of the components and railway bridges to critical factors other than train loads was introduced. To calculate the criticality of the components to train load and the vulnerability of the components to extreme events, the current condition of the components were determined through the inspection process. The recommendation for obtaining the relevant and sufficient information about the condition of the bridge through inspection was then made.

The future condition of a bridge and its components prone to environmental and fatigue effects, was evaluated using probabilistic methods. The prediction of the future condition of the components subjected to environmental factors and fatigue were conducted by other team members of the main project, the LCMRB, and the results of their work used as inputs in the method introduced in this research to identify the future ratings of the components associated with environment and fatigue. In this research, the ratings of components and the bridges at network level was conducted based on their current and future conditions. In addition, the criteria for determining the deadlines for taking action, including inspection repair and maintenance and performing structural analyses, were defined.

The outcomes of this research should satisfy the needs to:

1. Identify railway bridges and their components that are in most need of maintenance and rehabilitation actions based on their current and future condition at the network level;
2. Determine the deadlines for intervention for inspection, repair and maintenance and performing structural analyses, to ensure the safety and serviceability of the bridge;
3. Provide recommendations for timely usage of more costly inspection methods.

In addition, the outcomes of this research will be used to develop a method for identifying the number and frequency of inspections, and identifying the best methods for repair and maintenance. One of the key advantages of this method has to be its potential for improvement, as over time, more reliable data will be provided and more investigations will be conducted on the effects of each critical factor on railway bridges.

Developing a new rating method is essential, as through utilizing it among the thousands of components of bridges in a network, the scarce resources for repair will only be invested on the critical components which are in the worst condition. As a result, the very restricted resources available will only be invested to improve the safety and serviceability of bridges of a network which are in the worst condition. In addition, by incorporating the future condition of components into this new rating method and considering the criticality and vulnerability of the components, the efficient management of utilizing resources within the lifetime of bridges will be possible. In brief, efficiently utilizing resources for improving the safety and functionality of the railway bridges in a network will be the significant outcomes of this research.

1.3 THESIS OUTLINE

This thesis presents relevant literature (Chapter 2), the development of a synthetic rating method (Chapter 3), the dynamic effect of live (train) load on weighting factors of the components (Chapter 4), application of the synthetic rating method (Chapter 5), and conclusions and future work (Chapter 6). In Appendix A and B respectively, the algorithm of the synthetic rating method and publications derived from this research are presented.

In brief, Chapter 2 investigates different rating methods and identifies gaps in knowledge. Chapter 3 explains the proposed rating method and shows how the gaps in knowledge are covered by evaluating the contribution of each factor to bridge deterioration, and investigating the criticality and vulnerability of components by assigning weighting factors to them. Due to the importance of live load, Chapter 4 specifically focuses on quantifying the weighting factors associated with live load. Chapter 5 illustrates the practicality of the proposed synthetic rating method explained in Chapter 3 and its application on a network of railway bridges, and Chapter 6 presents the concluding remarks and proposes some topics for future research.

Chapter 2: Literature Review

This chapter reviews the literature on the following topics. Bridge inspection and monitoring systems (Section 2.1) focuses on methods for collecting data about railway bridges. Condition assessment and bridge rating (Section 2.2) identifies the methods for analysing the collected data to evaluate the condition of bridges. Criticality and vulnerability (Section 2.3) focuses on the contribution of factors towards bridge deterioration, the criticality of the bridge components, and vulnerability of the bridge to critical factors. Remaining service life (Section 2.4) reviews the methods for estimating the future condition of the components, and the summary (Section 2.5) highlights the implications from the literature impacting on this study.

2.1 BRIDGE INSPECTION AND MONITORING SYSTEMS

Railway bridges deteriorate over time due to environmental effects, changes in quality and magnitude of loads, etc. (Shih et al., 2009; Aflatooni et al., 2013b). There are many old bridges around the world that need rehabilitation (Elbehairy, 2007; Otter et al., 2012; Nielsen et al., 2013c). To ensure the safety and functionality of a bridge, its condition must be inspected or monitored and evaluated regularly. Having sufficient inventory data such as traffic volume information, structural characteristics, and bridge sketches, as well as reliable data gathered through inspection processes are essential requirements for the condition assessment of bridges (Akgül and Frangopol, 2003; Agrawal et al., 2010; Nukul and Bonaventure, 2010; Adhikari et al., 2012).

The condition of any components of a bridge may have an impact on the integrity of the structure or the safety (Laman and Guyer, 2010; Sutton et al., 2013). According to Austroads (2004), the ultimate aim of a bridge inspection is to understand the condition of its components. Outputs of the inspection process determine the priorities for repair and rehabilitation programs, basic evaluation prior to load rating, analysis of overload permit applications, and provide a continuous record of bridge condition and rate of deterioration (AASHTO, 2011).

Successful bridge inspection is dependent on proper planning and scheduling techniques, frequency of inspection, adequate equipment, the inspector’s qualifications and experience, and the cooperation between the inspector and other personnel in charge (AASHTO, 2011). According to FRA 2008 for railway bridges, in addition to the above factors, record retention and a system for reviewing the reports and tracking of critical deficiencies are also important for inspection process (Laman and Guyer, 2010).

Regular inspection reports of a bridge's condition make bridge engineers aware of any type of defects, such as damage from loading, fracture, eroded parts, etc. A precise and comprehensive recording process assists inspectors to identify and track the cause of the defects, including faults in design and calculations, poor quality of materials or inadequate supervision during construction, and enables engineers to assess maintenance requirements (Ryall, 2010). These reports should contain enough data for evaluating the current condition and predicting the future condition of the bridge, hence, they should be corrective and preventive (AASHTO, 2011). According to the BRIME Report (2001), preventing bridge deterioration could be more cost-effective than repairing them after being damaged. Reports should be clear and detailed, and encompass the date of the inspection, sketches of deteriorated members and photographs of defects, etc. Systematic numbering of bridge elements and using standard abbreviations assists inspectors to take notes easily (AASHTO, 2011).

Inspectors look for degradations and the extent of the damage. Bridges made from different materials may have different kinds of defects. For instance, some of the damage or defects in timber bridges are decay, insect attack and splits, which result in opening up within an element. In concrete bridges cracking, scaling, spalling, delamination, dampness, surface defects, patching and repairs, alkali aggregate reaction, and corrosion of reinforcement are the damages that are detected (Val and Melchers, 1997; MAIN ROADS WA, 2009; Adhikari et al., 2013). Defects in steel structures include corrosion, permanent deformations, cracking, and loose connections generally related to environmental condition or inappropriate quality control during construction (MAIN ROADS WA, 2009). Masonry bridges made of stones and bricks and bonded by mortar are subjected to the breakdown of their components over time. Cracking, splitting, spalling, disintegration, loss of mortar and stones, and damaged coated surface are the types of defects that can be found in masonry structures (MAIN ROADS WA, 2009).

Ryall (2010) believed that inspections should be conducted by, or at least under the supervision of, a professional engineer, because a great amount of experience and technical knowledge is required to accomplish an inspection in a systematic manner. In addition, Weykamp et al. (2009) argued that inspector's qualifications should be determined according to the type of the bridge and the complexity of its structure.

Consideration of these facts improves the quality of information gathered through inspection process.

2.1.1 Inspection Methods

Methods of inspection vary from visual inspection, where no instrument is needed, to the most detailed inspection or monitoring systems requiring different types of testing tools. Due to limited resources, a hierarchical system for inspection methods is adopted to avoid applying costly methods more frequently (Ryall, 2010; Sweeney and Unsworth, 2010). Visual inspection and Non-Destructive Testing (NDT) are essential in identifying and following the defects in structures (Onoufriou, 2002) and Structural Health Monitoring (SHM) is the most advanced method for monitoring the behaviour of the structure. This section of the literature review compares these methods from different perspectives, including practicality, economy and accuracy to identify and take into account their weakness and strengths for developing an efficient rating system.

2.1.1.1 Visual or Superficial Inspection

Visual is the first type of inspection used in currently available BMSs (Chiaramonte and Gattulli, 2005; Frangopol, 2011; Liu et al., 2011). It is the most economical method for identifying the types of defects that can be visually observed (McCann and Forde, 2001). This method is used more frequently than others and is effective when conducted by experienced and professional inspectors (Weykamp et al., 2009). Apart from its advantages, visual inspection has some drawbacks as well. For instance, it cannot be used for hidden elements or inaccessible areas such as foundations that are buried under the soil (Helmerich et al., 2008) or for masonry arch bridges where most parts of the structures are not visible (Orban, 2007; Orbán and Gutermann, 2009), or material damages like some types of cracks that are beneath the surface of the elements (Doebling et al., 1996; Weykamp et al., 2009).

Visual inspection only is not adequate for quantifying the amount of corrosion in a structural element, even if it is undertaken by a well-trained surveyor (Li and Chan, 2006). As a result of not being able to identify many types of defects via visual inspection, more costly methods, such as in depth inspections, are currently prescribed more frequently (Phares et al., 2001). The results of visual inspection are subjective and uncertain, as they are dependent on many factors such as the inspector’s experience, the definitions used for damages and interpretation of the subjective information (Tarighat and Miyamoto, 2009).

2.1.1.2 Non-Destructive Testing (NDT)

NDT techniques are used to search for hidden defects where visual inspection cannot be applied (Davey et al., 2012; Soliman et al., 2013). The investigations of Orbán and Gutermann (2009) showed that NDT was a reliable tool for evaluating the defects of the masonry structures such as internal voids, non-homogeneity, flaws, moisture contents, etc.

Although NDT is more reliable than visual inspection (Tarighat and Miyamoto, 2009), it has some disadvantages. Doebling et al. (1996) argued that technical devices used for inspection purposes were difficult to use in inaccessible components. Compared to visual inspection, these methods are significantly more costly. Therefore, selective use is required due to restricted financial resources (Onoufriou, 2002). The interpretation of the NDT results needs further research to increase its reliability (McCann and Forde, 2001; Orbán and Gutermann, 2009; Tarighat and Miyamoto, 2009). According to McCann and Forde's investigations (2001) in application of NDT methods, for each specific purpose with a certain amount of required precision, a relevant appropriate method should be selected. They added that in some cases, taking expert advice should be required. Karbhari and Ansari (2009) identified another drawback of NDT methods. They believed that non-destructive inspection tools developed for other industries could not be directly applied to the monitoring of civil structures.

2.1.1.3 Structural Health Monitoring (SHM) Systems

Another method for detecting damage in railway bridges due to environmental effects, ageing, or changes in load characteristics is SHM systems. Researchers have conducted many studies on SHM over the last two or three decades (Sohn, 2004; Chan and Wang, 2013; Wang et al., 2013). In Australia recent developments in SHM are summarized in the booked edited by Chan and Thambiratnam (2011). SHM systems have been used in many important bridges around the world such as Tsing Ma, Kap Shui Mun, and Ting Kau Bridges in Hong Kong, New Haengjou Bridge in Korea, Skarnsundet Bridge in Norway, and Storck's Bridge in Switzerland (Li and Chan, 2006).

SHM provides a continuous real time monitoring of the condition of the structure; therefore, sudden collapse of railway bridges can be prevented through detection of damages at the early stages (Shih et al., 2009). As an example of the sudden failure of railway bridges, collapse of the structure due to the failure of a pier subjected to flood forces can be noted (Reed et al., 2004). An ideal health monitoring system should identify the damage, show its location, determine the type of damage and its severity, and finally its impact on the behaviour of the civil structures (Li et al., 2009).

In this method the performance of the structure is also tracked and measured continuously or regularly for a sufficient period of time to identify deterioration, anomalies and damages (Catbas et al., 2008; Shih et al., 2009). SHM systems use a group of sensors for collecting response measurements and an algorithm for analysing and interpreting the measurements to evaluate the condition of a structure (Liang et al., 2001). Chan et al. (2011) believed that SHM systems should have two components: Structural Performance Monitoring (SPM) to monitor the performance of the structure at its serviceability limit states, and Structural Safety Evaluation (SSE) to evaluate the health status using analytical tools by assessing possible damages.

Aktan et al. (2002) believed that the analytical simulations such as SHM systems required a minimum standard in comparison to testing methods. They believed that there were currently not enough standards for comparing or combining the results of different analytical or experimental techniques, therefore, less dependency on specification and standards would be an advantage for SHM systems. Although NDT and monitoring technologies can assist in condition assessment of railway bridges, Weykamp et al. (2009) argued that their application as a routine method was still difficult due to their accessibility and complexity. They also believed that sufficiently appropriate guidance about their application was not currently available.

As shown in the above literature review, there are uncertainties in the results of visual inspection and NDT techniques. In addition, it is still not clear when it would be cost-effective to apply the more expensive methods or systems such as NDT or SHM. Furthermore, if they are not appropriately used, the results may not be reliable. For instance, if instead of NDT methods, visual inspection was used where there were hidden defects in the components, the results of the condition assessment would not be reliable and valid. As a result of the above discussion, rating systems should be improved simultaneously with advancement in technology to be capable of applying timely appropriate methods of inspection to achieve adequate reliability in their results by consuming the least amount of resources.

To achieve this aim, attempts should be made to improve the current rating systems by identifying the critical structural components of railway bridges using analytical approaches. Therefore, inspectors should predominantly conduct inspections on the critical components of the bridge using a more systematic and effective method.

To avoid increasing the cost of inspection, the higher levels of inspection processes should only be utilized when they are needed. In developing a reliable rating method, special attention should be paid to understanding the nature and characteristics of different critical factors that have influence on the condition of a bridge during its lifetime.

2.1.2 Inspection Categories

Different inspection categories have been defined by countries and agencies. For instance Austroads (2004) introduced a comprehensive 4-tiered inspection regime consisting of; “Routine; Condition Assessment; Structural Safety Assessment; and Load Capacity Assessment”. It covers the scope and frequency of bridge inspections, and responsibilities for accomplishing them. The Queensland Department of Main Roads (2004) introduced 3 levels of inspection. “Level 1 - Routine Maintenance Inspections; Level 2 - Bridge Condition Inspections, and Level 3 - Detailed Structural Engineering Inspections”.

In each level of inspection specific types of information can be obtained. In addition, the upper levels of inspection consume more resources such as equipment, time, and expertise. Therefore, the level of inspection recommended by the inspector has a direct impact on the cost of the project and on the accuracy of the results. As a result, recent bridge inspection manuals focus on the most critical situations. For instance, the American Highway Transportation Association (2011) and Washington State Bridge Inspection Manual (2010) have introduced more levels of inspection. They added the Fracture Critical Inspections level to pay special attention to the Fracture Critical Members (FCM) of the structure. FCMs are very important for the structure as any failure in them may cause the failure of a portion or the collapse of the whole structure (Catbas et al., 2008; Bridge Inspection Committee, 2010).

The above studies show that in order to manage the inspection process, the focus should be on the most critical conditions, elements, and factors. The tendency to apply the concept of criticality in current inspection manuals supports the idea that paying special attention to the most critical structural elements and crucial factors is a practical way to establish an efficient and viable inspection process and a rating system.

2.1.3 Inspection Frequencies

The frequency of inspection is determined according to the structure type, condition, age and the rate of deterioration (Queensland Dept. of Main Roads, 2004).

Some bridge evaluation manuals such as the American Highway Transportation Association (2011) mention that regular intervals of inspection should not exceed two years, however Weykamp et al. (2009) argued that according to quality assurance practices in Europe, longer inspection intervals of up to 20 years were acceptable. A less frequent but more detailed inspection may have a positive effect on the overall safety of bridges (Weykamp et al., 2009). Onoufriou (2002) argued that by increasing inspection intervals without paying attention to the most critical areas and appropriate techniques, the results of condition assessments of bridges would not be more reliable, and resources would be wasted. Therefore, in this research attempts were made to highlight the subject of criticality, to accomplish more detailed inspection only on critical elements and less inspections in general in order to increase the efficiency of the inspection process.

2.2 CONDITION ASSESSMENT AND BRIDGE RATING

2.2.1 Condition Assessment

Before commencing any work for design, repair, replacement, or rehabilitation, the condition of the railway bridges should be assessed based on data provided through inspection and monitoring methods. The condition evaluation of railway bridges should be based on a rational method and done in a systematic way (Sasmal and Ramanjaneyulu, 2008).

In condition assessment of bridges, both safety and serviceability are evaluated. Bridges may be functionally obsolete, although they are not structurally deficient (Western Builder, 2007). The sufficiency rating is related to rating bridges according to their serviceability. Load rating is another method for condition assessment of bridges and is based on their current load capacity (Laman and Guyer, 2010). Sufficiency and load rating are elaborated on later in section 2.2.2.

The condition of a bridge is derived by evaluating the condition of each individual component (Austroads, 2004). It is expressed in a numerical or descriptive form. In numerical form each condition state is given a number and at the end these numbers are used in conjunction with other factors to rate bridges for maintenance, etc. (Ryall, 2010). In a descriptive form, inspection manuals provide a descriptive definition for each condition level and the inspector identifies the condition level accordingly based on the current condition. For instance in Australia, VicRoads uses numerical values and RMS NSW utilizes a brief description for each condition (Austroads, 2004).

Wang and Elhag (2008) explained different condition assessment descriptions in different bridge management systems.

The number of condition states for different structural components such as superstructure and substructure can differ according to their accessibility. For example, Laman & Guyer (2010) defined more superstructure condition state levels than substructure. For some types of structures such as masonry bridges, design knowledge is limited and condition assessments can be difficult (Orbán and Gutermann, 2009).

It appears that the results of condition assessments of bridges in current BMSs is highly dependent on the experience and knowledge of inspectors, the definition of different condition state levels, the interpretation of the outputs of the equipment, accessibility to the elements and judgments based on descriptive information. In addition, the effect of the condition of each structural element of a bridge on the integrity of the structure has not been accurately identified.

In each of the above items and many others, there is considerable ambiguity and uncertainty (Tarighat and Miyamoto, 2009), therefore, it is important to find a method to deal with these uncertainties. For this purpose, in this research the different condition states are defined based on the importance of the element. By concentrating on the most critical components of the railway bridge and conducting more complex structural analyses on bridges, which are subjected to more critical factors, the uncertainty will decrease and the reliability of condition assessment will enhance.

2.2.2 Bridge Rating Methods

Timely performance of appropriate rehabilitation, strengthening or upgrading for the right bridge is dependent on an appropriate system that rates railway bridges based on their structural condition (Nukul and Bonaventure, 2010). A rating system is a part of a prioritization process. Prioritizing bridges is based on the condition of elements at the time of inspection, reliability to provide a safely continued service, remaining service life, risk related to probability and the consequences of failure of a structural element, socio-economic related to economic and relevant social issues, and bridge sufficiency indicators, which are related to the serviceability of the structure such as bridge width, bridge vertical clearance, bridge load carrying capacity, and bridge barrier condition (Austroads, 2004; Zayed et al., 2007; Laman and Guyer, 2010).

When rating bridges, factors associated with the structural conditions are considered, and for prioritization based on the risk assessment, the impacts of other non-structural factors for making decisions, such as human, economic and social factors are also taken into account. As explained earlier, in a bridge rating system the first step is to evaluate the condition of the structural components of a bridge, which deteriorate over time. A weighting factor is assigned according to the importance of each structural component for the integrity of the structure. Finally, based on the condition of the components and related weighting factor, the bridge rating in a network of bridges is identified. Rating of bridges can also be based on their functionality, called a Sufficiency Rating (SR). It shows the current serviceability level of a bridge with a respect to its original condition (Bridge Inspection Committee, 2010). Current rating methods for existing bridges are mostly based partly on engineering analysis and partly on practical experience (Xu et al., 2009). In this section, some of these methods will be explained and their advantages and disadvantages will be identified.

2.2.2.1 Weighted Sum Model (WSM) Method

WSM is a popular decision making model; however, it is appropriate for single-dimensional problems only. In this method each alternative A* will be rated by using the following equation (Triantaphyllou et al., 1997; Sasmal and Ramanjaneyulu, 2008).

$$A^*_{wsm} = \sum_{j=1}^{N} a_{ij} W_j \qquad \text{for } i=1, 2, \ldots, M \qquad \sum_{j=1}^{N} W_j = 1 \tag{2.1}$$

M is number of alternatives, N is number of criteria, a_{ij} is the measure of performance of the ith alternative in terms of the jth decision criterion, and W_j is the weight of importance of the jth criterion.

In a bridge rating system A* can be the condition of the whole bridge and a_i is the condition of component i, and W_j is the importance of that component for the integrity of the structure. Because this equation is one dimensional, it is not able to consider the weightings of different components of bridges, associated with different factors (e.g. flood, wind, collision, earthquake and environmental effects, which contribute to bridge deterioration).

2.2.2.2 Weighted Product Model (WPM) Method

WPM is similar to the WSM method; however, for each criterion alternatives are compared with each other (Sasmal and Ramanjaneyulu, 2008). As mentioned earlier, these models were proposed in 1967 and 1969 respectively, and are appropriate for single-dimensional problems only (Sasmal and Ramanjaneyulu, 2008). The results of these methods cannot be used for bridge rating purposes where many other factors, including the criticality of the components for the integrity of the structure are involved.

2.2.2.3 France Method

According to Bevc et al. (1999), in the French rating system, for each bridge three main parts are considered including i) equipment (in the original wording, it could be more appropriate to call it 'non-structural components') such as barriers, drainage systems, footpaths, etc., ii) piers and bearings consisting of columns, walls, foundation, bearings, and iii) decks such as slabs on longitudinal girders, cantilever slabs, transverse beams, etc. Then for each part, the extent of the damage is identified and an archive of these defects with their description is recorded. Finally, the bridge rating will be accomplished according to a classification with a few classes using particular descriptions about the overall bridge condition.

2.2.2.4 United Kingdom Method

Based on Bevc et al. (1999) and Ryall’s (2010) explanations, in the UK rating method, each bridge is broken down to its elements, then for every single element a condition factor is defined. The location of each component, showing its structural importance, is considered. Finally, by considering road factor the Maintenance Priority Number (MPN) is calculated.

2.2.2.5 Japan Method

In Japan, each element in the structure is evaluated based on every single kind of defect, such as cracking, corrosion, etc., then a demerit rating is assigned to each element in a tabular format (Laman and Guyer, 2010; Ryall, 2010). According to Laman and Guyer (2010) and Ryall’s (2010) explanations, the Bridge Condition Rating (BCR) is assessed and rated based on its element’s condition. BCR is compared with a condition rating provided by experienced bridge inspectors and the rehabilitation plans for each bridge are consequently prepared (Laman and Guyer, 2010; Ryall, 2010). Performance of bridges is evaluated in J-BMS, and a rehabilitation strategy is offered for minimum maintenance cost and maximum quality (Miyamoto et al., 2001).

The above four rating systems are too simplified and do not consider the vulnerability of the structure to different critical factors. In addition, the criticality of the components for the integrity of the structure is not assessed reliably by conducting structural analyses. Although the simplicity is an advantage of these methods because these methods are too subjective, as evidenced by the interviewed inspectors and engineers in this research, they are not fully applied in real practice. Nowadays, with the availability of modern computers with powerful processors, new methods can be developed that are able to take into account different critical factors for evaluating the condition of a bridge and producing results that are more reliable. However, the logic of the process should be simple and understandable for the user and the procedure should be simple to follow and carry out.

A more reliable rating system for railway bridges will enable engineers and managers to use their resources more efficiently. The simplicity of the above methods can be used in developing a new rating method. In addition, special attention should be paid to the potential of improvement of the developed system in conjunction with the adequacy of the information in the BMS database.

2.2.2.6 BRIME Method (BRIME REPORT, 2001)

BRIME stands for **Bri**dge **M**anagement in **E**urope and is a project funded by the European commission and conducted by the national highway research laboratories in the United Kingdom, France, Germany, Norway, Slovenia and Spain. The BRIME method follows an optimization procedure in three levels. In the first level, the structural conditions of bridges are assessed and the best time for intervention for maintenance or repair actions are determined. If sufficient funds are available this level is used for prioritizing bridges for maintenance and repair action. However, insufficiency of funding is always a problem, therefore, as a result other factors in other levels should be taken into account. The second level is conducted by introducing a safety index β. This safety index includes the remaining service life of the bridge, importance of the structure and condition assessment. The third level of optimization is based on different maintenance strategies and the cost associated with them. This optimization can be for a single bridge, at project level or at the network level.

Because BRIME considers different factors at different levels, its results are more reliable, however, it still does not appropriately consider the effect of critical factors on important structural elements. Therefore, by focusing on the above critical factors including the live load, lateral loads, fatigue, and environmental effects and their different impacts on the integrity of the bridge or the bridge deterioration rate in developing a new rating method for railway bridges, the outcome will be more reliable and cost-effective.

2.2.2.7 New York Method

According to Ryall's (2010) explanations, in the New York approach all components of a bridge are inspected regularly and rated. Component rating is done by assigning a number from '1 = failed' to '7 = new' according to their condition assessment results. A weighting factor is designated to each bridge component. Ultimately, the overall bridge condition rating (BCR) is calculated by Eq. 2.2.

$$BCR = \frac{\sum(Component\ rating \times Weight)}{\sum Weights} \tag{2.2}$$

The New York method simply explains the condition of a bridge using cardinal data (Wang and Elhag, 2008). Similar to the first four methods, this method also does not consider different critical factors and the types of loads in defining the weighting factors associated with them to produce reliable results about the current condition, and predicting the future condition of the bridge.

2.2.2.8 The VicRoads Method

Austroads (2004) describes the VicRoads method. VicRoads (2003) adopts a similar method to the New York method. To eliminate the NY's weaknesses VicRoads introduced an Average Group Rating (AGR). AGR is for a group of elements such as piers, span, etc. and can be calculated by Eq. 2.3:

$$AGR = \frac{\sum\left(2 \times ACR + E^{1/2}\right)}{(Number\ of\ \ Elements)} \tag{2.3}$$

AGR depends on the exposure factor (E), and ACR. ACR is the Average Condition Rating of each critical element and is calculated by Eq. 2.4.

$$ACR = \sum(Condition\ state\ number \times Condition\ \%)/100 \tag{2.4}$$

Ultimately the Bridge Condition Number (BCN) is calculated by Eq. 2.5. W_b is defined as an important weighting factor applied to the element group.

$$BCN = \sum\left(AGR \times W_b\right) \tag{2.5}$$

In this method the criticality of the elements (components as mentioned in this thesis) are considered as importance weighting factors for a group of elements. However, the structural configuration of different bridges, including their geometries and materials, are not taken into account in an appropriate way. In other words, in this method, to one type of component (e.g. column or beam), without considering the geometry of the structure, always one particular number is allocated as importance weighting factor (W_b). The material of components is considered by multiplying a number to the weighting factors. These numbers do not change based on the environmental condition of the bridge location, so the effect of different environmental conditions on different materials are not into account. In addition, the vulnerability of the elements to the critical loads for evaluating the future condition of the bridge has not been included for rating bridges. It means that W_b will not change when the structure is subjected to different loads. Therefore, paying inadequate attention to the current and future condition of the structure has been found to be a drawback and was taken into account when developing a new rating system in this research.

2.2.2.9 PONTIS Method

In the PONTIS condition rating, each structure including bridge, culvert, etc., is divided to 5 groups in terms of their structural function, and six groups based on their materials. A number of elements for each group are then defined. For each element up to 5 different conditions are described and based on this descriptive information they are rated numerically according to the severity and extent of the deterioration (Mn/DOT.US, 2009).

2.2.2.10 Austroads Method

Based on the Austroads (2004) method, the consequences of failure of a structural element in a bridge and assessing its probability are shown using a risk index. Factors such as element location, condition and its criticality, environment, loading and design are considered when developing the risk index. The probability of failure is dependent on factors such as loading, resistance, condition, inspection, and exposure factor. The consequences of failure can be assessed by factors like the seriousness of the injury or death of people, environmental issues, traffic access, economy, and road class factors. Bridge condition as a major factor, as well as current bridge capacity, rate of degradation, and loss of capacity will have effects on the priority for maintenance and bridge repair proposals.

In the above PONTIS and Austroads approaches for analysing the criticality of the elements and vulnerability of the structures, the contributions of different critical factors towards bridge deterioration are not taken into account. In order to consider the contribution of different factors, the risk associated with each of them should be calculated, as they cause bridge deterioration to different extents based on the location of the bridge. The overall contributions should then be evaluated using a sound method. Moreover, the criticality and vulnerability of the components are not evaluated by performing appropriate structural analyses. It is therefore required to take into account the criticality of the elements of the bridge, geometry, loading and materials of the bridge elements to develop a sound rating system for a network of bridges.

2.2.2.11 Chiaramonte and Gattulli Method

According to Chiaramonte and Gattulli’s (2005) method, a rating system for railway bridges is based on the argument that the overall condition of a bridge cannot simply be evaluated by a summation of the effects of damages of each component, as different types of material and structural systems are also required to be considered and compared. Therefore, a condition function V_D is defined which can be seen in Eq. 2.6. This condition function considers the failure importance F_i, member importance K_{mi}, intensity factor K_{di}, extent factor K_{ei}, and the urgency or evolution factor K_{ui}. F_i indicates the impact of defect *i* on the durability and safety of the structural member.

$$V_D = \sum_{i=1}^{n_d} F_i \times K_{mi} \times K_{di} \times K_{ei} \times K_{ui} \tag{2.6}$$

The location of each defect is identified by dividing the structure into its components and sub components. The evaluation factor is defined for each defect and for each component through summation of the condition of each sub component. “If-then” rules for each type of factor such as intensity, extension, evolution are defined. The effective components, the ideal components for the above factors, are then defined to make the comparison between bridges with similar characteristics but with a different number of components possible. The effective deficiencies for effective components are calculated using the developed formula. Finally, the condition evaluation index Eq. 2.7 is defined to compare the level of deficiency. This index is based on the overall rating of the effective deficiency of a whole or a part of a railway bridge.

$$\mathfrak{I} = \frac{\mathfrak{R}}{\mathfrak{R}_r} = \frac{\sum_{j=1}^{n_{ce}} V_{Dj}^{e}}{\sum_{j=1}^{n_{ce}} V_{D,ref}^{e}} \tag{2.7}$$

$\mathfrak{I}$ is the condition index, V_{Dj}^{e} is the effective overall deficiency for the *j*th-component; $\mathfrak{R}$ is the overall rating of the effective deficiency of the observed structural system (e.g., overall bridge, a selected single span, a selected set of systems), assembled through the subset of the n_{ce} effective components; $\mathfrak{N}_r$ is the rating reference summation where all the effective components defined in the database are at the maximum deficiency.

This method is based on identifying the level of the deficiency of the components of the bridge. The advantage of this method is that by defining an effective component the comparison between different bridges will be possible. This can be used for rating a group of bridges. However, the method does not take into account the vulnerability of the bridge towards different critical factors. In addition, the contribution of different critical factors towards bridge deterioration are not considered, and the practicality of the method for rating a network of bridges is not investigated.

2.2.2.12 Pennsylvania Method

In prioritizing bridges according to the Pennsylvania method as described by Laman and Guyer (2010), rating bridges based on their conditions is considered in terms of the probability of failure. Other factors such as human, environmental, economic, etc., are then considered as consequences of failure. Finally, the risk associated with the probability and the consequences of failure is calculated for the purpose of prioritization as follows:

$$\text{Risk} = \text{Probability} \times \text{Consequence} \tag{2.8}$$

As in this research, the focus is on the condition rating, therefore, the part which is considered as consequences of failure will not be explained. The probability of failure is calculated through Eq. 2.9:

$$\begin{aligned} \text{Probability of Failure} &= 1 - \sum_{i=1}^{n} \left[\frac{W_i (PP)_i}{N_i} \right] \\ &= 1 - \left[\frac{W_R R}{1} + \frac{W_{Sb} Sb}{4} + \frac{W_{Sc} (K_1 K_2) Sc}{4} + \frac{W_F F}{10} \right] \end{aligned} \tag{2.9}$$

R: Bridge Reserve

S_p: Super-structure Condition

S_b: Sub-structure Condition

S_c: Scour

K_1: Bridge Type factor

W_R: Reserve Weighting Factor

W_{Sb}: Sub-structure Condition weighting factor

W_F: Fatigue weighting factor

W_{Sc}: Scour weighting factor

K_2: Bridge foundation type factor

To calculate Bridge Reserve (*R*), four interrelated parameters including loading (*L*), capacity (*C*), superstructure condition (*Sp*) and age (A) are taken into account. Bridge Reserve in this method is the difference between the capacity of the bridge and the load applied to the bridge, multiplied by the superstructure condition and the bridge age factors. This method is one of the most reliable methods, among others, as it considers important factors such as loading, capacity, age of the bridge, scour and fatigue; however, the effect of other loads, including lateral loads such as wind and earthquake on the bridge and its components are not considered. Moreover, the importance of critical factors such as extreme events in degrading bridges are not taken into account.

Table 2-1 shows the advantages and disadvantages of some of the main different rating methods mentioned in Section 2.2.2. Evaluating the strengths and weaknesses of different methods will assist in finding a more reliable method, which at the same time is practical to be applied to a network of bridges.

Table 2-1 Advantages and disadvantages of different rating methods

Methods	**Advantages**	**Disadvantages**
Methods based on WSM	Simplicity.	Cannot consider different factors that cause deterioration in bridges and also the different criticality and vulnerability of components associated with relevant critical factors and different structural geometries.
BRIME	Considers different factors more appropriately by placing them in different levels.	Does not efficiently take into account the vulnerability of the structure to different critical factors by utilizing a reliable method such as structural analyses.
VicRoads	Simplicity, and roughly considers the material and criticality for elements, but not sufficiently reliable.	Does not consider different factors that cause deterioration in bridges and also the different criticality of components associated with relevant critical factors and different structural geometries.
Chiaramonte and Gattulli (2005)	To some extent, this method is able to compare different bridges with different numbers of components at the network level.	The contribution of different critical factors towards a degrading structure and the vulnerability of the bridge to each critical factor are not taken into account.
Pennsylvania	This method considers important factors such as loading, capacity, age of bridge, scour and fatigue. It also considers the correlation between some factors.	The method can be improved by considering the vulnerability of bridges to different lateral loads, such as earthquake, wind, and collisions, and evaluating the contribution of each critical factor towards the bridge’s deterioration.

2.2.3 Intelligent Systems for Rating Bridges

In recent years, intelligent systems such as neural networks and fuzzy logic have been used for rating bridges. These systems were developed recently due to the availability of modern computers capable of manipulating large amounts of inspection data to tackle the uncertainties that arise from engineering judgments during inspection processes in traditional rating methods (BRIME REPORT, 2001).

2.2.3.1 Methods Based on Neural Network Models

An Artificial Neural Network (ANN) builds a relationship on existing data using a series of logical steps to understand the relationship of a set of output results and given input values (Mehrjoo et al., 2008; Laman and Guyer, 2010). The main drawback of ANN methods is that they are case dependent. This means that if it is developed for a particular network it cannot be used for another database. In designing and identifying the parameters of ANN, many uncertainties are incorporated into the model due to the different number of neurons and layers, defining learning rules, etc. (Wang and Elhag, 2007). In addition, it needs a large database or very accurate description of the structural element conditions (BRIME REPORT, 2001). To identify the relationships in neural network models a large amount of information from too many bridges is required (Wang and Elhag, 2008). The result of the Wang and Elhag study (2008) showed that their neural network models could not take into account uncertainties associated with subjective ratings in a reliable way and also could not evaluate the overall condition of a bridge structure with a full description. It can be seen that the dependency of this method on large databases and other drawbacks mentioned above make this method impractical and consequently inappropriate for the method of rating railway bridges in this thesis, which has taken into account different critical factors and rated bridges based on their current and future condition. However, for evaluating the future condition of each bridge component in a network, considering that currently many investigations are conducted to improve the Neural Network Models (e.g. Son et al., 2010; Bu et al., 2012), they can be appropriate to be used to predict the remaining service life of the bridge.

2.2.3.2 Analytic Hierarchy Process (AHP) and Fuzzy Logic

AHP is a multiobjective, multicriterion and multifactor decision-making method for ranking systems and can be used for planning inspections, and prioritizing maintenance and repair actions (Harker and Vargas, 1987; Melhem and Aturaliya, 1996). Since the 1970s, researchers have conducted many studies based on AHP (Harker and Vargas, 1987; Saaty, 1988; Kuzman et al., 2013). Saaty (1980) developed this method (Sasmal and Ramanjaneyulu, 2008) and Zahedi (1986) conducted a comprehensive investigation on the methodology of AHP and its applications. The feasibility of using the AHP method was shown by Xu et al. (2009) in the synthetic rating of a long suspension bridge.

AHP builds a hierarchical structure to solve a complex problem. It splits a general problem, which is the goal of the project, into sub-problems. The priorities between the alternatives of the sub-problems are then easily identified, and finally, these priorities are synthesized to determine the overall priorities between the alternatives of the main problem (Wong, 2006).

Many advantages of the AHP method have been mentioned by scholars. For instance, by using pair wise matrices and calculating the eigenvalue and corresponding eigenvector the overall ratings are more efficient and consistent (Melhem and Aturaliya, 1996). Simplicity and its extensive application in tackling complicated decision making processes are its other advantages (Sasmal and Ramanjaneyulu, 2008; Ren et al., 2013). AHP can be used for single or multi-layer decision making processes as it uses relative values rather than actual ones (Sasmal and Ramanjaneyulu, 2008). Another advantage of this method is that every element in a level should not necessarily be a criterion for the elements of the next level. In other words, a hierarchy is not required to be complete (Saaty, 1990). Each level in AHP can represent one aspect of a problem.

In the AHP method, different levels for different factors can be added or eliminated (Saaty, 1990). This allows for the elimination of elements whose effects may not be very significant, and consequently this method is very efficient for criticality and vulnerability analysis. According to Zahedi (1986), Saaty considered the limitation of this method to be that the number of the elements at each level should not exceed nine, although it is not a compulsory condition for all applications. Sasmal and Ramanjaneyulu (2008) utilized the Multi-Attributive Decision Making Model (MADM) to overcome this problem. They believed that MADM method could be used for as many bridges as were available and the condition of the components could be calculated more accurately. However the drawback of this method is that every element of a bridge should be inspected and the inspector must be 100% confident with the results of his work (Wang and Elhag, 2008). It is therefore dependent on inspector observation and the results of tests (Sasmal and Ramanjaneyulu, 2008).The other restriction of AHP is that the accuracy of this method is dependent on the precision of pair-wise weights (Zahedi, 1986).

For the rating method developed in this thesis, the number of critical factors did not exceed the limit mentioned above, they were also located in different levels according to their characteristics. In addition, in order to compare them in a pair-wise comparison matrix, previous risk analyses conducted by standards were used to incorporate the accuracy of their calculation into this rating system.

Fuzzy logic models have been used with AHP to consider the uncertainties that come from visual inspection, NDT results, etc. (Tarighat and Miyamoto, 2009) and handling the subjective information (Sasmal and Ramanjaneyulu, 2008) that comes from them. According to Tee (1988) fuzzy logic was developed by Zadeh in 1965. Fuzzy logic is used in many fields associated with artificial intelligence, including engineering, economics, and human decision processes (Zadeh, 1975; Ertuğrul and Karakaşoğlu, 2009; Pourghasemi et al., 2012). Bridge condition assessment and rating is a decision making process where both objective and subjective data are used. Objective or quantitative data includes items such as the dimension of a beam, which is measurable or countable; however, subjective data are qualitative information, for example the extent of corrosion in a steel member of a bridge or the experience of an inspector (Tee, 1988). Fuzzy set theory is a systematic way of dealing with objective and subjective data (Tee, 1988). It is used in translating descriptive information to numerical to express the condition more specifically (Zadeh, 1975).

According to this review of the literature the AHP methods has many advantages for rating railway bridges, as it gives the best prioritization for the weightings associated with the critical factors. The ability to define different criteria as investigated by Sasmal and Ramanjaneyulu (2008) proves that this method can model a bridge rating process involving many factors. However, utilizing fuzzy logic at a network level of bridges can significantly reduce the practicality of the method, as it is too complex and requires a large database, as well as accurate data from inspection process. Therefore, fuzzy logic was not used to develop a practical rating method in this thesis.

2.2.4 Bridge Load Capacity Rating

In addition to bridge condition assessments for evaluating the structural and functional condition of bridges, load rating calculations and reliability approaches are carried out to analyse the overload permit applications or as an indication of the safety of a bridge (AASHTO, 2011). Load rating, along with durability assessment of the materials of a bridge, is used for developing the maintenance actions (Kawamura and Miyamoto, 2003).

Load rating is accomplished based on the live load capacity of the bridge in the Australian Standard (2004). The concept of rating in Australian Standard AS 5100.7 is based on limits for both ultimate and serviceability states (Wang et al., 2009). For the ultimate state the actions with 5% probability of being exceeded over the lifetime of the structure, and for the serviceability state the actions with 5% probability of being exceeded in one year, are considered (Wang et al., 2009). The rating in strength limit is performed by considering all actions including moment, compression, and shear in critical sections, and for the serviceability limit state, the deflection and vibrations are checked (Wang et al., 2009).

The ultimate aim in load rating is to determine the safe live load capacity of a bridge using a series of calculations (LeBeau and Wadia-Fascetti, 2007; Bell et al., 2013). Load rating is recommended for new bridges, or throughout the life of a bridge, based upon the inspection information (Mn/DOT.US, 2009). The load ratings results are used to determine whether the bridge should be repaired or strengthened or the operation of a bridge should be limited (AASHTO, 2011). In evaluating the load capacity of a bridge, critical components and consequently their effects on the structure are required to be assessed (Australian Standard, 2004). The quality of and accessibility to available information about the current condition of the bridge and its loading data directly affects the precision and reliability of the results of the load rating process (AASHTO, 2011).

According to Austroads (2002), the outcomes of the load rating will assist asset management systems to:

- More profoundly apprehend the bridge behaviour under live loads;
- Determine the members that are required to be strengthened;
- Improve the maintenance approaches and processes;
- Prioritise bridges for maintenance and repair or rehabilitation;
- Anticipate the remaining service life of bridges; and
- Remove load or speed restrictions from bridges as much as possible.

The reliability analysis is known as the most consistent indicator for safety of a bridge or its elements (Neves et al., 2004) and is seen as a realistic approach (Minervino et al., 2004). It considers redundancy in a structure and the relationship between failure modes (Estes and Frangopol, 2005). However, in reliability analysis the calculations are more complex and their results can be affected by manipulating the input data (Estes and Frangopol, 2005). In addition, a large amount of input data, which may not be available, is required in reliability analysis (Estes and Frangopol, 2005). Frangopol and Akgul (2004) showed that some elements that had the same reliability index had very different rating factors.

Currently, to avoid explicit reliability assessment, the limit states philosophy which is based on the reliability principles used in bridge rating systems to check the safety limits in deterministic way (Wang et al., 2009). Ultimate limit states are utilized for checking the safety limits (Wang et al., 2009). In the Load and Resistance Factor Rating (LRFR) method (AASHTO, 2003), the drawbacks of the load rating method have been corrected by introducing the load and resistance factor. This factor considers the effects of uncertainties of different loads such as earthquake, wind, and vehicle effects (Wang et al., 2009). In addition, in LRFR, which is a deterministic method, the philosophy of the reliability approach is incorporated as a result of being compatible with Load and Resistance Factor Design (LRFD) specifications (AASHTO, 2003). LRFD determines reliability limits in design for the purpose of identifying more accurate safety levels for relevant limit states (Wang et al., 2009).

From the above review of the literature, it can be concluded that by utilizing the principal of analytical methods such as load rating and LRFR, which are applied to selected bridges, a reliable method for calculating the weighing factors can be developed. Here weighting factors refer to those currently used in subjective approaches of the condition assessment of bridges. Taking into account the rapid advancements in developing finite element software, which assist in modelling bridges in a faster and more convenient way than before, the practicality of the introduced rating method can be maintained.

2.3 CRITICALITY AND VULNERABILITY

2.3.1 Importance of Critical Factors

Many factors are involved in the deteriorating condition of railway bridges over time. Live load is constantly applied to the structure, and the criticality of the current condition of the railway bridge is related to that. Other factors contributing to degrading bridges over time include loads associated with the extreme events, such as flood, wind, earthquake, collision, and those factors which gradually degrade the structure over time, including environmental factors and fatigue. Environmental factors encompass many factors such as corrosion, temperature changes, termite attack, wear, etc. Depending on the type of loads, including live load or extreme event loads, the criticality and vulnerability of components will change (Aflatooni et al., 2012a, 2012b).

Flood is one of the important factors contributing to bridge failure (Schmocker and Hager, 2011; Papanicolaou et al., 2012; Zhang et al., 2013). Researchers have conducted many investigations into the effect of scour on substructures (Hager and Unger, 2010; Ni et al., 2011; Kumar et al., 2012), and the impact of flood on superstructures (Schmocker and Hager, 2011). Because the removal of the bed soil around the foundations, piers or abutments due to scour may lead to sudden catastrophic failure, researchers have recently developed different monitoring systems for timely detection of scour (Lin et al., 2010; Fisher et al., 2013; Lin et al., 2013).

Earthquake effects on bridges is critical in many parts of the world (Aygün et al., 2010; Kawashima et al., 2011; Wotherspoon et al., 2011). Investigations showed that the vulnerability of bridges to earthquake increases in flood-prone regions (Lu et al., 2010; Banerjee and Ganesh Prasad, 2013; Prasad and Banerjee, 2013). Varuma et al. (2011) investigated the effect of aging on the behaviour of bridges to seismic forces. Alvarez et al. (2012) studied the changes in axial forces caused by seismic forces in long-span arch bridges. Researchers such as Konstantakopoulos et al. (2012) investigated the combination of the effects of moving loads and earthquakes, and Akiyamaa et al. (2013) studied the behaviour of the retrofitted bridge to seismic excitations.

Wind effect is critical for long-span bridges, and as a result, researchers have conducted many investigations into it (Guo et al., 2010; Chen et al., 2011a; Yang et al., 2012). Studies showed the importance of the wind load on the fatigue life of the long-span suspension bridges and proposed methods to monitor their structural condition over time (Chen et al., 2011b; Petrini and Bontempi, 2011; Ye et al., 2012). Researchers' investigations showed that the effect of severe wind, such as hurricanes, on different types of bridges were mainly on those bridges located in coastal areas or prone to tsunami (Robertson et al., 2007; Padgett et al., 2012).

Collision is another critical factor that damages bridges. Ship collision, which occurs on large bridges, has been studied by researchers (Yun et al., 2008; Fan et al., 2011; Wang, L. et al., 2012). However, for the majority of railway bridges overpassing roads with a less complex structure, vehicular impact is important. The current studies on vehicular impacts showed their considerable contribution towards damaging bridges

(El-Tawil et al., 2005; Hai, 2006; Xia et al., 2012). Different industries developed strategies to tackle the vehicular impact problem (Ghose, 2009). Song et al. (2007) developed a health monitoring method to detect vehicular impact and evaluate the extent of the damage.

For the above factors, which will not occur on a regular basis, the severity and probability of their occurrence are important.

Fatigue is another important factor that significantly contributes to degrading bridges with steel components (Chan et al., 2003a; Li et al., 2003a; Lee, H. H. et al., 2012; Zhou et al., 2013). The cumulative fatigue damage, which is the sum of the damage in all previous years for the critical element of a bridge, must be calculated for bridge rating based on fatigue effects (Australian Standard, 2004). According to Australian Standard AS 5100.7 (Wang et al., 2009) nominal fatigue life is defined for rating bridges based on the fatigue limit state, and this nominal fatigue life is estimated by evaluating the aggregated fatigue damage at the critical components.

Researchers have conducted may studies on the effect of fatigue on bridges (Pellegrino et al., 2010; Imam et al., 2012; Sousa et al., 2013) and determined the residual life of them (Caglayan et al., 2009; Marques et al., 2010; Cremona et al., 2013). Damages in fatigue-critical components are increased as a result of overloading bridges during time (Polepeddi and Mohammadi, 2000; Laman and Guyer, 2010). Leander et al. (2010) explained the method for fatigue assessment of a railway bridge and Pipinato et al. (2011) investigated the fatigue evaluation of bridges in the presence of earthquake load. Li et al. (2002) showed that the impact of typhoon loading on fatigue damage was more significant than live loading.

Environmental factors contribute to bridge deterioration gradually. Environmental effects encompass many factors such as corrosion, carbonation, wear, termite attack, and temperature changes.

Corrosion is one of the important agents in degrading bridges (Appuhamy et al., 2011; Huang et al., 2012; Bertolini et al., 2013). Researchers attempted to detect and quantify the corrosion of components (Bhadra et al., 2010; Jensen et al., 2013) and predict the remaining life of corroded components of bridges (Heinemeyer and Feldmann, 2011; Pipinato et al., 2012). Many investigations have been conducted to identify the effect of corrosion on bridges (Brencich and Gambarotta, 2009; Pipinato et al., 2012; Cavaco et al., 2013; Ou et al., 2013). In environments where the level of carbon dioxide was high, studies showed that corrosion induced by carbonation was significant (Ann et al., 2010; Stewart et al., 2011). Changes in temperature is another critical factor that contributes to the deteriorating condition of railway bridges (Xu et al., 2010; Ren et al., 2011; Casciati et al., 2013). For timber bridges, rot or decay of timber components due to different factors, such as termite attack, effect the safety and durability of the bridges (Ranjith et al., 2011; Moore et al., 2012a; Moore et al., 2012b).

All of the above fatigue and environmental factors gradually degrade the structure, and are significantly interrelated. The above study on different critical factors shows that different factors contribute to degrading the bridges in different ways, therefore, appropriate methods should be developed to estimate their contribution towards bridge deterioration.

2.3.2 Criticality of Components and Condition of Bridges

In every BMS, one of the most important aims is to determine whether the bridge is safe and serviceable to credible live load, as bridges conditions deteriorate with age. To assess the condition of the bridge, engineers and researchers pay special attention to the critical components of the bridge. This is because a) considering all components are costly (Wang and Elhag, 2008), and b) the structural behaviour of a bridge and its ultimate capacity is mainly dependant on the condition of its critical components (Australian Standard, 2004; Austroads, 2004).

Kim (2001) believed that the critical structural components of railway bridges were those which experienced the maximum stress ranges above their endurance level. Many documents and inspection manuals introduce Fracture Critical Members (FCMs) (Catbas et al., 2008; Bridge Inspection Committee, 2010). The information about the different types of FCMs is provided in AASHTO LRFD Bridge Design Specifications (AASHTO, 2011). Criticality can be based on the position of the load, for instance Boothby (2001) showed the critical load case and its location in a masonry arch bridge had the most severe effects on the structure. The findings of Catbas et al. (2007) showed that by using a structural monitoring system for damage detection the response of a structure, including forces, deformations, and stresses under the live loads in critical locations of bridges, could be identified with high level of reliability.

The degree of the criticality of the structural elements is identified by weighting factors (Austroads, 2004). The criticality rating (CR) used by VicRoads is based on structural group and material element weighting factors. RMS NSW defines critical elements based on their contribution to the strength of the bridge in three levels. These levels are called Critical Element Rating (CER) levels and are in descriptive form. As has been noted, the above inspection manuals consider the criticality of the elements according to their materials and type of the component (e.g. superstructure or substructure, etc.). However, they do not take into account the geometry of the structure that will change the structural role of each component. Furthermore, in identifying the criticality of the components, they do not take into consideration the type of loads applied to the structure.

In order to evaluate the criticality of the components in carrying live load, investigating the dynamic effect of the load on the railway bridges is essential. Many researchers have studied the dynamic behaviour of bridges to live load (Chan and O'Connor, 1990; Memory et al., 1995; Kwark et al., 2004; Sieffert et al., 2006). Chan et al. (2003c, 2003b) investigated the bridge responses to twisting and pitching modes. Xia et al. (2000) investigated the dynamic behaviour of suspension bridges under train loads. Their studies showed that the dynamic interaction between the bridge and train was not significant. Fryba (1996, 1999) thoroughly explained the vibration of structures and dynamics of railway bridges. Xia et al. (2000) developed formulations for a three dimensional model of a suspension bridge and applied it to an existing long span suspension bridge. The results did not show any significant interaction between the train and the real bridge. Kim (2011) conducted experimental studies to investigate the influence of track structure including rail, sleeper, and ballast on the railway bridge.

Lee et al. (2006) evaluated the dynamic response of a monorail bridge by establishing a procedure, including analytical, experimental and field test. According to their investigations, the reason for the lateral displacement of the monorail bridge was that torsional loads were applied to the bridge due to the eccentricity between the vertical load of the train and the shear centre of the bridge. The focus of all of the above studies was on some particular modes or only on some specific responses. The effects of the increase of the speed or load of the train considering the ultimate capacity of the critical components of the bridge were not investigated in the above studies.

The analytical and experimental investigations of Senthilvasan et al. (2002) on a curved bridge depicted the effect of the speed of a moving vehicle on the Dynamic Amplifications Factor (DAF). This study showed that DAFs would not necessarily increase with the speed of vehicle. DAF indicates the increase in the response of a bridge due to the dynamic effect of the motion of a single moving load and does not consider the resonance effect of a moving load with multiple axles (Liu et al., 2009a).

The resonant vibration of railway bridges was investigated by Xia et al. (2006). The outcome of their research identified the natural frequencies of the train motion, the train shape and the axle spacings, the span length and the stiffness of the bridge in lateral and vertical directions as the main parameters for resonant vibration of railway bridges. The studies of Liu et al. (2009b) identified the speed of the train, the bridge damping ratio, the vehicle by bridge mass ratio, and the vehicle by bridge natural frequency ratio as the factors which had significant impact on the dynamic behaviour of the bridge.

The investigations of Majka and Hartnett (2008) showed that damping of the vehicle did not have a considerable impact on the response of the bridge. According to the studies mentioned above, the parameters, which have significant impact on the dynamic behaviour of the bridge and resonance in vibration, were identified, but the impact of this resonant vibration on the critical components of the bridge still requires investigation. Therefore, it can be concluded that the focus of the past research was on evaluating the dynamic response of the bridge when it was subjected to train loads. The effect on internal forces such as moment, axial, shear or the combination of them induced by train loads, with respect to the capacity of different components was not taken into consideration. In other words, the susceptibility of the different critical structural components of the bridge to the changing magnitude of the train load and/or the speed of the train were not taken into account (Aflatooni et al., 2013a).

2.3.3 Vulnerability of Components and Bridges

There are different definitions for vulnerability. The vulnerability may refer to the whole structure or the vulnerability of the critical elements of the structure. Lind (1995) defined vulnerability as “the ratio of the failure probability of damaged system to the failure probability of the undamaged system”. Suna et al. (2010) believed that the vulnerability was the structural behaviour sensitivity to local damage, and Austroads (2004) considered the vulnerability of critical elements to different factors such as traffic crashes.

Structures can be vulnerable to some types of loads. For instance many studies (e.g. Shamsabadi et al., 2007; Borzi et al., 2008; Polese et al., 2008), have undertaken vulnerability studies on different types of structures to earthquake loads. The vulnerability of the structures with even small damages can be high when they are subjected to some specific types of loads (Nanhai and Jihong, 2011).

Structures, especially bridges that have a long lifetime, can also be vulnerable to environmental factors. The American Highway Transportation Association (2011) identified the vulnerability of some elements of a structure to some factors. For instance, elements vulnerable to corrosion are steel piers and their joints and splices, cable connections, rivets, and bolts. Timber piles are vulnerable to marine organisms where they are in salt water. Footing piles are very vulnerable when they are exposed to scour, and pins and hangers are vulnerable to corrosion, the movement of the hanger or shear fracture in the pin and fractures in hanger.

The vulnerability of the elements or the vulnerability of the bridge change due to different crucial factors. For instance, the Bridge Inspection Committee of Washington (2010) defined criteria for bridges that were vulnerable to scour. The American Highway Transportation Association (2011) investigated that spread footings were more vulnerable than piles where they were subjected to scour and erosion and concluded that special consideration was required for them.

Vulnerability of structural elements may change when they are subjected to different types of actions. Some load cases for some particular structures are critical. For example, wind is a critical load for long span bridges, or according to reliability indices, the maximum temperature difference can sometimes be the most critical load case for the structural components or overall structural behaviour (Catbas et al., 2008).

Vulnerability analyses are preformed to identify the weak points in the structure, and effectively used for identifying the important elements of the structure (Nanhai and Jihong, 2011). Almost all rating systems are founded on critical factors or critical structural elements. In addition, their rating and condition assessment are based on the vulnerability of the structure to the critical factors, although these terms have not been directly mentioned. However, they do not take into account different critical factors and do not reliably estimate the contribution of each critical factor towards bridge deterioration. Moreover, the weighting factors associated with the criticality and vulnerability of the components that they define to be applied at the network level of bridges are subjective and unreliable.

According to recent developments, in order to determine the critical elements of a single railway bridge, different types of analyses and factors have been taken into account. For instance, to assess a fracture critical member among load path, internal, and structural redundancies, only load path was considered by the Washington bridge inspection manual (2010). Wong (2006) identified 5 factors to determine the criticality of the elements in the Tsing Ma cable-bridge, and introduced four steps for criticality and vulnerability analysis for the Tsing Ma bridge. His aim was to show the feasibility of this method. Firstly, he classified the structural components into 15 groups and 55 components, then 5 criticality and 3 vulnerability factors were identified as follows:

1. Alternative load paths, identified based on the redundancy of a structural component. The redundancy of the critical components is low.
2. Maximum design stress, which shows the strength reliability of a structural component.
3. Remaining life based on the fatigue reliability of a structural component.
4. The presence of imperfections that do not require immediate repair and will be identified based on previous recorded inspection data.
5. Failure mechanisms that for each structural component are identified based on the ultimate load-carrying capacity under the maximum load condition.

According to Wong’s (2006) investigations, corrosion, damage and wear are introduced as vulnerability factors. Based on the degree of exposure, likelihood of detection in superficial inspection, and the influence on structural integrity, he defined the different categories for a vulnerability rating. The criticality and vulnerability analysis were then conducted individually based on the summation of different factors and the results were synthesized to rate the components of the bridge for inspection intervals and required corrective and preventive actions.

The rating process of the above method did not consider the correlation between factors and was required to be improved. Therefore, to increase the accuracy of the rating, after setting up the criticality criteria based on the above criticality factors and vulnerability criteria according to vulnerability factors, AHP was used by Xu et al. (2009) to define the hierarchy process and determining the priorities.

Pair-wise matrixes were used for each criticality and vulnerability factor to determine their weights through Eigenvalue and Eigenvector calculation. For synthesizing the results of the criticality and vulnerability for each structural component Xu et al. (2009) adopted fuzzy logic and membership function to take into account the uncertainties associated with criticality and vulnerability factors. Tee (1988) elaborated the fuzzy operators and Tseng et al. (1992) explained the membership functions. Van Laarhoven et al. (1983) described the triangular fuzzy numbers and the consistency of the matrix was discussed by Triantaphyllou et al. (1997).

The criticality and vulnerability factors mentioned here were used for rating the components of a single bridge, however, for rating a network of bridges this method seems to be too sophisticated to be used in practice. It can be concluded that a modification of this method is required for it to be reasonably simplified.

As it can be observed from the literature review, AHP can be a very powerful method for categorizing different factors based on their characteristics. Zayed et al. (2007) used the AHP method for rating a network of bridges with unknown foundations. He defined the risk index R. This risk index was calculated by considering risk parameters including the weight of each factor and its associated worth factor. Weight factors are calculated based on AHP method and Eigenvector of a pair-wise matrix. The worth factor, which shows the overall contribution of each risk factor, is calculated by using the utility function approach. The weight of the risk factor does not change with project as it shows the importance of each risk factor with the respect to others. The calculated R represents the type of actions that are required to be taken, including replacement, rehabilitation, or foundation investigation level or monitoring.

The results of the Zayed et al. (2007) investigations indicated the ability of the AHP method to be used for rating railway bridges at the network level. However, it is limited to bridges with unknown foundation and should therefore be modified to be applicable for rating a network of railway bridges. It is important to define curial risk factors and their weighting factors to serve the purpose of rating a network of bridges. In addition, the importance of critical factors should be calculated based on the unique characteristics of each factor. The vulnerability of components and the bridge should be estimated for each critical factor.

2.4 REMAINING SERVICE LIFE

The collapse of some bridges shows the importance of predicting the remaining service life of bridges for implementing the appropriate maintenance at the right time (Kim, 2001). Bridge deterioration should be determined at early stages to increase the remaining service life of bridges (Weykamp et al., 2009). Deterioration can cause loss of serviceability, load carrying capacity, aesthetic value or diminishing the safety, and increasing limitations for traffic (BRIME REPORT, 2001). With precise and timely prediction of the future condition of a bridge, a more appropriate cost/benefit assessment of a bridge can be conducted for a life cycle management (Catbas et al., 2008). The progressive rate of deterioration of bridge elements, from superficial cracks or minor surface defects, to the loss of a section or even significant structural issues, can be anticipated using several disciplines including visual inspection, and reliable sampling testing methods (Austroads, 2004). In addition, engineers try to predict the condition of the critical components using different methods such as Markov chains and Weibull-distribution and improving them (Agrawal et al., 2010).

The definition stated by Austroads (2004) for remaining service life is "the estimated number of years with continued routine maintenance and projected loading, until the bridge is expected to require rehabilitation, strengthening or other upgrading, or replacement". To identify the service life of a bridge the minimum acceptable limit of performance will be defined (BRIME REPORT, 2001). The performance may be represented by the condition rating or the load carrying capacity (BRIME REPORT, 2001).

2.4.1 Deterioration Agents

Anticipating the remaining service life of a bridge requires adequate and accurate data. Researchers have conducted many investigations to identify the remaining service life of the components of bridges (Dissanayake and Karunananda, 2008; Cusson et al., 2011; Chen and Huang, 2013). The effect of critical factors and different load patterns and intensity on structure, various structural types and forms, design and detailing, quality of materials and construction, and many other factors were taken into account to predict the level of degradation in bridges and the remaining life of bridges (Val and Melchers, 1997; Li et al., 2003b; Ryall, 2010). To see the progress of deterioration, the historical data of a bridge needs to be available (Nukul and Bonaventure, 2010).

2.4.2 Remaining Service Life Prediction Models

The future condition of the bridge elements are predicted by various deterioration models (Austroads Publication, 2002; Jiang, 2010; Wang, R. et al., 2012). These models can be deterministic, probabilistic or mechanistic. In deterministic models a mathematical algorithm is given for predicting the condition of the bridge elements; however, in probabilistic models the deterioration rate is unknown as probabilistic phenomena (Austroads Publication, 2002). The mechanistic-based models need quantitative contribution of complex phenomena such as steel corrosion, cracking, fatigue, shrinkage and creep, etc. (Agrawal et al., 2010). The explanations of some models based on deterministic, probabilistic or mechanistic principals, as well as their advantages and disadvantages are discussed below.

2.4.2.1 Regression Models

Regression analysis predicts the deterioration rate based on an equation (Austroads Publication, 2002). The results are dependent on the ability to produce this equation and its parameters. This equation should be the best fit to a set of data, therefore, the availability and the quality of data is important (Austroads Publication, 2002). The parameters of the equation may include current condition, material type, carried out repair actions, traffic loading, environmental effects (Austroads Publication, 2002). These deterministic methods are not able to reliably predict the bridge condition as many uncertainties involve these parameters. Therefore, probabilistic models are proposed to take these uncertainties into account (Lounis and Madanat, 2002; Imam et al., 2008).

2.4.2.2 Markov Process

Markov processes as a state based stochastic model are the most appropriate for modelling deterioration rate with uncertainty over time. Moreover, they efficiently model the bridge condition from one condition state to another with probabilistic analysis (Laman and Guyer, 2010). The meaning of state-based in Markov and semi-Markov processes is that the probability that a condition of a bridge in a given time changes is evaluated. Types of variables considered include traffic loading, design specification and maintenance history, and environmental condition (Lounis and Madanat, 2002).

According to Lounis and Madanat’s (2002) investigations, Markov processes are practical; however, they have drawbacks as well. They believed that in these models the condition rating was predominantly based on the qualitative data from visual inspection and not from quantitative data such as stress conditions, structural responses, or material characteristics. To overcome this problem, other deterioration models that were based on reliability such as Mechanistic models were developed. Mechanistic models evaluate the performance of the bridge based on quantitative parameters. However, considering too many failure modes and their consequences makes this method less practical, especially when too many bridges are supposed to be evaluated at a network level (Lounis and Madanat, 2002).

2.4.2.3 Neural Network Models

As previously mentioned in Section 2.2.3.1, neural network models can assist to improve the reliability of the prediction of the future condition of bridges and their components. Researchers have conducted many studies to predict the deterioration rate of the components using neural network methods (Morcous and Lounis, 2005; Huang, 2010; Bu et al., 2012). One of the difficulties in identifying the remaining service life of the bridge components is the lack of historical data about the condition of the bridge components. Lee et al. (2008) developed a Backward Prediction Model (BPM) to generate historical data by using the available inspection records. Lee et al. (2012) combined BPM with the Delay Neural Networks (TDNNs) technique to predict the long-term condition of bridge components. The literature shows that the neural network may be used as a tool to predict the future condition of the components.

2.4.3 Maintenance and Rehabilitation Strategies

To improve the condition of a bridge according to priorities, appropriate maintenance and rehabilitation strategies should be selected to increase the remaining service life of a bridge. Member replacement is a popular approach of maintenance (Kong and Frangopol, 2004) for increasing the remaining service life of a structure. Neves et al. (2004) proposed a method that replaces one or more components of a bridge and the probability of failure is analysed. In this model, bridges are modelled as combinations of components, not a single component, because failure of one element does not normally end in the collapse of a structure. The results revealed that the effect of the correlation between components on the probability of failure was considerable. In the short-term, replacement of elements is the most cost-effective strategy.

Petcherdchoo et al. (2004) recommended a combination of maintenance actions. The result of their investigation depicted that a combination of maintenance actions could reduce the maintenance cost and at the same time improve the level of safety in a bridge. As each maintenance action individually has its own weak and strong points, combining them can be more satisfactory.

Kim’s (2001) investigation indicated that the impacts of fatigue on railway bridges due to the higher ratio of live load to dead load was more critical than road bridges. Nowadays, new materials such as Fiber-reinforced Polymer (FRP) are used for retrofitting the structures. Shahrooz and Boy’s (2004) research identified their durability in the short term in reinforced concrete bridges; however their long-term behaviour requires investigation.

The reason for reviewing the literature on remaining service life and maintenance strategies (Sections 2.4.2 and 2.4.3) is to show the connection of this current study with other parts of the LCMRB project.

2.5 CONCLUDING REMARKS

The literature review investigated the different aspects of current bridge condition assessment and rating systems, and highlighted their advantages and deficiencies to enable the establishment of a practical and reliable rating method for a network of railway bridges. Literature on inspection and monitoring systems shows the uncertainties and ambiguities in the outcomes of different inspection methods. The uncertainties come from the dependencies of the outcomes due to the inspectors' experience, difficulties in the interpretation of the NDT results, inaccessibility to different components of the bridge, insufficiency of the data provided through inspection, and subjectivity in the definition of different condition states. Based on current inspection methods, the appropriate time for inspection and the timely usage of costly methods are not clear.

The review of the literature on the condition assessment and bridge rating methods identifies the subjectivity of the methods used in determining the weighting factors. Weighting factors show the criticality of the components. Not taking into account the geometry and material of the structure in determining the weighting factors, is the main reason for subjectivity. In intelligent systems for rating bridges, AHP has been found to be a practical method for decision making. Other methods such as ANN and fuzzy logic are impractical to be used for rating a network of bridges, where massive amount of variables that degrade the structure, such as different structural configurations, loads, and critical factors, are involved.

The review of the literature on the criticality and vulnerability section determines the critical factors that affect the current and future conditions of the bridge. It shows that each critical factor degrades the structure in its unique way. Investigations on the topics of criticality and vulnerability show that the current rating methods, which can be applied to a network of bridges, do not take into account the following:

1) The criticality of the components for the integrity of the bridge structure in carrying live loads at both safety and serviceability levels,

2) The vulnerability of the bridge to critical factors including environmental effects, fatigue, and extreme events such as flood, collision, earthquake and wind, and
3) The contribution of different critical factors towards bridge deterioration.

Investigations on the impact of live load on the structures show that the susceptibility of the critical components of the bridge to the dynamic effect of live load on the railway bridge is significant and should be taken into account in identifying the criticality of the components.

The advanced condition assessment and rating methods, which are capable of taking into consideration the importance of critical factors and criticality and vulnerability of the components, are suitable only to be applied to a single selected bridge, as they are complex and costly when applied to a network of bridges. However, the principle of these methods after simplification can be taken into account to develop a reliable method for rating a network of railway bridges.

The review of literature on the remaining service life and maintenance strategies shows the link between this research and the LCMRB project, in which this research took part. In order to have an influential contribution in knowledge, this research developed a practical and reliable method for condition assessment and rating of railway bridges at the network level.

In this research, new equations for rating bridges were introduced. In developing the rating equations, the simplicity of the current practical methods for rating a network of bridges, as well as the reliability of the methods used for particular bridges were taken into account. The rating method based on the above rating equations took into account the current and future conditions of the railway bridges at network level, as well as the importance of critical factors and criticality and vulnerability of the components and bridges.

According to the literature, AHP is a practical and simple method, which can be efficiently used to prioritise the contribution of critical factors towards bridge deterioration. To quantify the criticality of extreme events, incorporating the available knowledge in risk assessment of the hazards used in design standards can significantly improve the reliability of the introduced method.

The review of the literature depicts that the structural configuration of bridges including geometry, material, connections between components, condition and loading should be taken into consideration to identify the weighting factors. Therefore, the proposed rating method should take into account the criticality of the components of the bridge by conducting structural analyses and identifying the demand by capacity ratios of the components. The concept of structural analyses needs to be derived from existing structural analysis methods, such as the load rating method. To take into account the vulnerability of the bridge and its components to different critical factors in this method, different weighting factors should be calculated. The practicality of the method can be maintained by performing structural analyses and using their results as constants over a long period of time.

By identifying the critical components of railway bridges, the reliable methods of inspection and monitoring will specifically focus on them and therefore, the resources will be invested in a cost-effective way. The proposed rating method should have the potential for improvement over time by incorporating the outcomes of investigations in the form of new weighting factors or enhancing the reliability of the existing weightings. The potential for improvement is important because identifying the effect of all environmental factors needs extensive time and resources, and can be conducted in the long run. Currently the results of different investigations cannot be incorporated into the rating system, hence, the proposed method should be able to establish a platform to use the outcomes of the research in a systematic way.

Chapter 3: Development of the Synthetic Rating Method

This chapter presents the overview of the synthetic rating method (Section 3.1), synthetic rating equations (Section 3.2), identification and quantification of critical factors (Section 3.3), quantification of weighting factors (Section 3.4), synthetic rating procedures (SRP) (Section 3.5), and concluding remarks (Section 3.6). The main publication that arose from this chapter can be seen in the reference list (Aflatooni et al., 2014).

3.1 OVERVIEW OF THE METHOD

The review of the literature identified that in order to develop a rating method which could identify the railway bridges in the worst structural condition among a network, based on both their current and future conditions, the following points should be taken into account:

1) As the method is a preliminary assessment and should be applied to a network of perhaps thousands of bridges, it should be simple and least costly,
2) The method should be less subjective than current existing methods,
3) The critical factors causing bridge deterioration should be identified,
~~4)~~ The contribution of critical factors towards bridge deterioration should be quantified,
5) The criticalities and vulnerabilities of the components and the bridge and their ratings towards different critical factors should be investigated.

This rating method narrows down the entire bridge stock and their components in a network to a limited number, called a preliminary assessment. After identifying the limited number of bridges, detailed inspection and structural evaluation will be possible considering the available budget. In order to maintain the simplicity and practicality of the method, the concept of using weighting factors from the current practical method was adopted in this method. To reduce the subjectivity of the method, decision making tools such as the Analytic Hierarchy Process (AHP), risk assessment conducted in the design standards, and more reliable methods of assessment such as structural analysis, were used.

Bridges should be safe to carry loads and serviceable not only at the time of assessment, but also during their whole life, hence, the durability of the bridge should also be taken into account. Different critical factors that contribute towards bridge deterioration should therefore be identified first. The way that each critical factor degrades the structure and the extent of the damages associated with them differ. Therefore, the contribution of different factors towards bridge deterioration should be quantified in different ways. The existing rating methods do not appropriately consider the different factors that contribute to bridge deterioration. This is because there are too many factors, and quantification of their contribution towards bridge deterioration is not easy, especially considering that many of them are inter-related. Although many investigations have been conducted on each critical factor, the current existing rating methods still cannot predict the future condition of bridges and their components considering the effect of all important factors at the same time. The above explanations motivated the author of this thesis to develop a method to identify and quantify the importance of factors in Section 3.3. The details of the method, the philosophy behind each part, and the reasons showing that this proposed method is practical and more reliable than current existing methods are discussed throughout different sections of this chapter. The parameters associated with the importance of factors are taken into account in the synthetic rating equations in Section 3.2. As will be explained in Section 3.2, the future condition of the bridge components deteriorated by environmental factors and fatigue was predicted by the researchers of the main project (LCMRB) who were working on the remaining service potential of bridges and were incorporated as an input in the synthetic rating equations.

The condition of the whole structure of a bridge is related to each component of the bridge. The importance of each component for the stability of the whole bridge (e.g. the criticality and vulnerability of the component) changes when the bridge is subjected to different loads. Current rating methods applicable to a network of bridges do not appropriately take into account the criticality and vulnerability of a bridge components subjected to different loads by using reliable tools such as structural analysis and SHM systems. This drawback of the current existing rating systems results in investing available scarce resources on unimportant components or those components still capable of carrying loads. The reason is that for the sake of simplicity the current rating systems are reluctant to involve structural analysis in their assessment systems. After very critically reviewing the literature and observing the capabilities of the current BMSs used across the world and the capabilities of the industry partners of the main project the LCMRB, it was identified that structural analysis could be used to identify the criticalities and vulnerabilities of the components of the bridge to different loads. However, it should be conducted as less frequently as possible for practical reasons. Performing structural analysis will assist in taking into account the available real capacities of the components and bridges of a network in a far more reliable way than current existing rating methods. In addition, the SHM systems can be used to determine the criticality and vulnerability of the components through measurement with a very high level of reliability. The criticality and vulnerability of the components will be incorporated into the synthetic rating equations (shown in Section 3.2) through the weighting factors. The details of the method for quantifying the weighting factors and the reasons that show the synthetic rating method is much more reliable than those used in current existing rating systems are discussed in more details in Sections 3.4 and 3.5 and chapters 5 and 6 of this thesis.

Based on the above brief explanation, the synthetic rating equations and the method for synthetic rating were developed in this research. The inputs of the method were the inspection records on the condition of the components, the anticipated future condition of the components calculated using probabilistic methods, the loads applied to the structure, and the environmental condition at the location of the bridge.

The synthetic rating method takes into account the importance of critical factors and criticality and vulnerability of the components. Therefore, contrary to current existing rating methods, instead of a single rate, different rates for each component of a bridge are calculated. Each rate shows the criticality or vulnerability of the components to one critical factor. The vulnerability of the whole bridge associated with each factor is then calculated. The future condition of the bridge is calculated by synthesizing the vulnerability of the bridge to each critical factor. The method developed in this research is called the synthetic rating method because the rating related to the future condition of the bridge is calculated based on combining the different ratings associated with different critical factors. In addition, the overall rating is calculated based on the current and future ratings of the bridge.

Figure 3-1 shows the overview of the method and involvement of the different components.

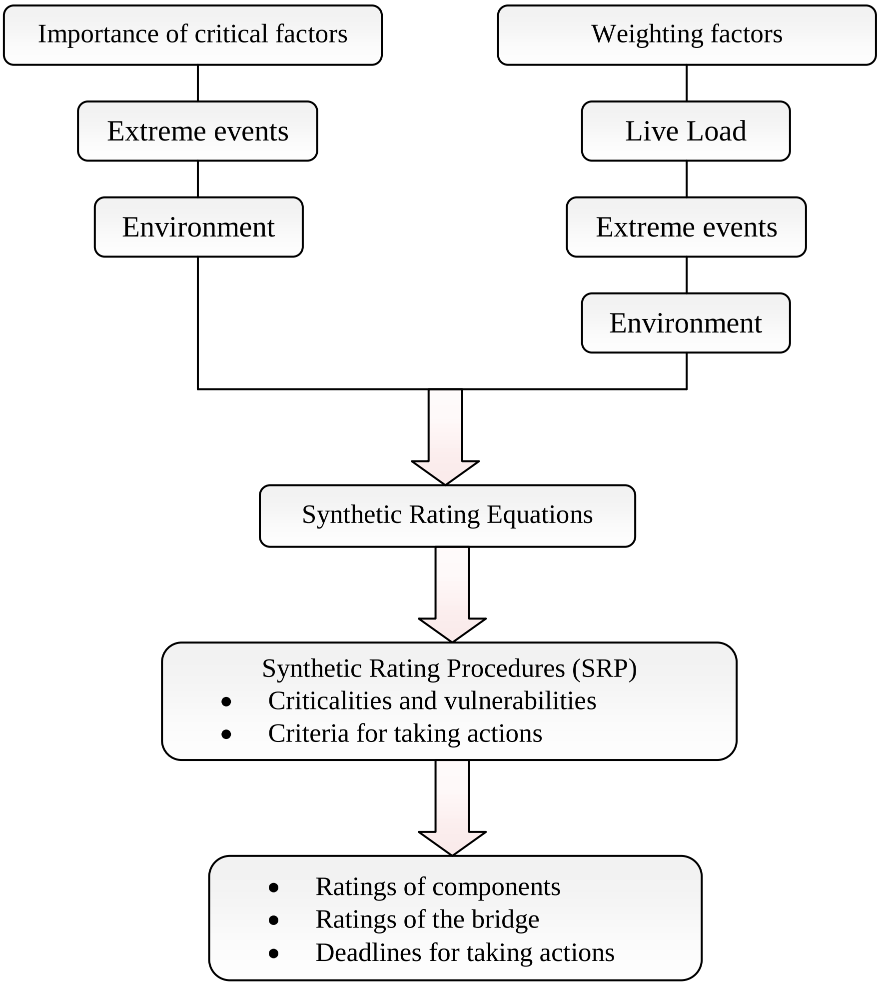

Figure 3-1 Overview of the synthetic rating method

Different parts of Figure 3-1will be elaborated on in the following sections of this chapter.

3.2 SYNTHETIC RATING EQUATIONS

This section presents the development of synthetic rating equations (Eqs. 3.1 - 3.3). They are called synthetic rating equations because they take into account the effect of the combination of different critical factors on each bridge in the network, and they consider both the current and future conditions of the bridge. The concept of weighting factors from current exiting methods that are used in practice was considered in these equations. In the equations, the concept of criticality and vulnerability of a bridge and its components in a network to different critical factors were considered. In developing the synthetic rating equations, the following points were taken into account.

1) Must be applicable to bridges with different numbers of components.

2) To maintain the practicality of the method, the condition of the bridges should be assessed based on the available data on the condition of the components in BMS database.
3) The method should include the contribution of the critical factors towards bridge deterioration, the criticality and vulnerability of the components.

Synthetic rating equations include parameters related to the importance of critical factors (e.g. $\alpha_{fl}, \alpha_w, \alpha_e, \alpha_{col}, \beta_{ev}$), and parameters related to the criticality and vulnerability of components (e.g. weighting factors $al_i, afl_i, aw_i, ae_i, acol_i$). To quantify the parameters associated with the importance of critical factors, the risks related to the severity and probability of occurrence of each critical factor are taken into account. In calculating the weighing factors, the response of the structure to different critical factor is taken into consideration. The novel methods for quantifying the above parameters are discussed in Sections 3.3 and 3.4. Eq. 3.1 determines the current condition of the bridge and indicates whether the structure concerned is safe and serviceable for carrying live loads. Eq. 3.2 shows the future condition of the bridge, and Eq. 3.3 takes into account the current and future condition of the bridge.

$$BCCR = \frac{10}{n}\sum_{i=1}^{n} C_{ci} al_i \tag{3.1}$$

$$BFCR = \frac{10}{n}(\alpha_{fl}\sum_{i=1}^{n} C_{ci} afl_i + \alpha_w \sum_{i=1}^{n} C_{ci} aw_i + \alpha_e \sum_{i=1}^{n} C_{ci} ae_i + \alpha_{col}\sum_{i=1}^{n} C_{ci} acol_i + \beta_{ev}\sum_{i=1}^{n} C_{fi} al_i) \tag{3.2}$$

$$BOCR = \gamma_1 BCCR + \gamma_2 BFCR \tag{3.3}$$

Where; al_i: Weighting factor related to component i and associated with live load.

- $BCCR$: Bridge current condition and rating
- $BFCR$: Bridge future condition and rating
- $BOCR$: Bridge overall condition and rating which is a value that reflects the current and future condition of the bridge
- γ_1, γ_2 : Coefficients which incorporate the managers' decisions in the equations. They are calculated through Eqs. 3.21 and 3.22, which are explained later in this thesis
- n : Number of components

- $\alpha_{fl}, \alpha_w, \alpha_e, \alpha_{col}, \beta_{ev}$: Coefficients that respectively show the criticality of flood, wind, earthquake, collision, and environmental effects, and are prioritised by *AHP* method
- $afl_i, aw_i, ae_i, acol_i$: Weighting factors associated with component i, that are respectively related to flood, wind, earthquake, and collision
- C_{ci}: Current condition of the i th component, identified from inspection (a number from 1 to 5)

C_{fi} : Future condition of the i th component, identified by prediction of deterioration rate equations (a number from 1 to 5).

The criticality of the components for the whole structure needs to be determined in Eq. 3.1. In order to enable comparison of different bridges with different numbers of components, the factor $10/n$ is introduced in Eqs. 3.1 and 3.2. The number of the inspected components (n), can be any number and there is no limit for that. Many of the components of bridges are costly to be accessed, and their conditions are not recorded in the inspection report, by using $10/n$ in the Eqs. 3.1 and 3.2 and making them insensitive to the number of components, the judgement on the condition of the bridge can be made based on the available data on the condition of their components. However, for each bridge, it will be recommended to inspect all critical components of the bridge, if sufficient budget is available.

The number 10 in the coefficient ($10/n$) could be any number and it is not related to the limit of components. However, as the number of bridges in the network could be thousands, and for each component, the associated bridge, and each critical factor, a unique number for rating them are calculated, the number 10 in the coefficient ($10/n$) is considered to be able to help provide a wider range in the criteria for taking action and to avoid too many digits after the decimal point.

Each part of Eq. 3.2 is associated with one critical factor and is quantified in a different manner in this research, as the factors cause deterioration in bridges in different ways. For extreme events, such as flood, wind, earthquake and collision, the probabilities of their occurrence are important. The risk associated with these factors can be simply calculated using available standards as will be shown in Section 3.3. The factors related to these extreme events are not related to each other, as any of them may take place in different time and places. However, any changes in the condition of components due to any of them and after the event, will be recorded by the inspector as a new condition of the components, and C_{ci} parameters will be calculated based on that. The parameter C_{ci} will be incorporated into all terms of the Eq. 3.2, related to the extreme events. In addition, the effect of the new condition of the component will be indirectly taken into account on the vulnerability of the structure to environment.

The last part of this equation, related to the environmental effects, included many different factors such as corrosion, temperature effects, wear, termite attack and many others. These environmental factors, along with fatigue, degrade the structure gradually, and many of them are inter-related. As a result, these factors were introduced as a single term in the second equation, as quantifying each of them and investigating the correlation between them individually is extremely difficult and requires enormous amounts of time and resources to accomplish. As a result, less reliable methods such as the Markov Chain, explained in Section 2.4.2, are used as a practical solution to estimate the future condition of the components and the coefficient related to that (e.g. C_{fi}). The Markov Chain is a state-based model and can capture the correlation between all environmental factors and fatigue. Parameter C_{fi} is determined using Table 3-21, which will be explained later in Section 3.5. In Table 3-21, the future condition of the components (CMav) was the only input to be calculated by other researchers in the LCMRB project, who were working on the future condition of the components. The future rating of each bridge component is determined in this thesis based on its future condition and its vulnerability to environmental factors. The details of different ratings will be discussed later in Section 3.5.

According to the method introduced in this section, the correlations between extreme events and environmental factors and fatigue are taken into account. To explain these correlations, for instance when scour occurs due to flood, the parameter associated with the current condition of the foundation component C_{ci} changes, then C_{fi}, which is a parameter related to the future condition of the component changes too. Because C_{fi} is calculated based on Markov Chain method, and according to Markov Chain method C_{fi} will be calculated based on C_{ci} and the transition probabilistic matrix. Then the new C_{fi} is used in the last term of the Eq. 3.2 and as a result the correlation between the vulnerability of the structure to environment and the flood, is taken into account. This also applies to other extreme events and environmental and fatigue factors.

Eq. 3.3 provides a rating for the bridge in network of railway bridges based on its current and future conditions. The judgment about the health and durability of each component and bridge in the network is made based on each part of Eqs. 3.1 - 3.3 and will be explained later in Section 3.5.

3.3 IDENTIFICATION AND QUANTIFICATION OF CRITICAL FACTORS

This section outlines the identification of the critical factors and elaborates the method introduced for quantifying the importance of critical factors. The importance of each critical factor shows the contribution of each factor towards bridge deterioration.

3.3.1 Identification of Critical Factors

In order to identify the critical factors that contribute to bridge deterioration, the data provided by the industries involved in managing railway bridges, and the review of the literature were taken into consideration. The critical factors identified from the above two sources were live (train) load, fatigue, environmental effects, and flood, collision, earthquake, and wind loads. Environmental factors encompass many factors, such as corrosion of steel components, carbonation, effect of temperature, termite attack on timber bridges, etc. The effects of the critical factors on materials such as steel, concrete, timber, etc. are different. The contributions of critical factors toward bridge deterioration also change based on the location of the bridges in different parts of the world. For instance earthquake can be a very important factor for some countries, but not significant for others. Therefore, for the area of each network of railway bridges specific investigations on the severity and the risk of each critical factor should be taken into account. The following survey was conducted to identify the importance of critical factors in an area in Australia.

3.3.2 Survey and Results

The inspection and inventory data of 1122 railway bridges within an urban area of Australia were collected from the bridge asset management database of a bridge authority. The temperature in the urban area was considerably changeable. The area included different types of roads, with different levels of traffic volume. Some preliminary statistical analyses were then conducted. As can be observed in Figure 3-2 more than 70% of bridges were older than 40 years. This means that many of them could require maintenance and repair and they were vulnerable to critical factors.

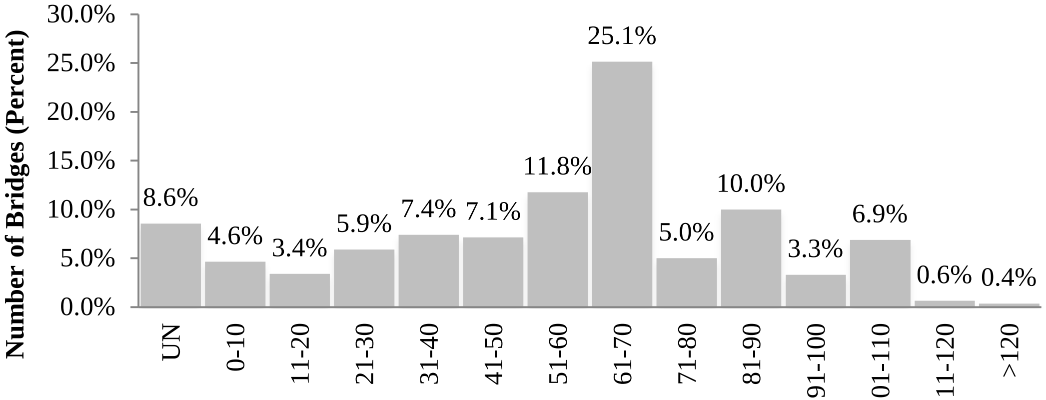

Figure 3-2 Distribution of ages of railway bridges in Australia

According to Figure 3-3 steel was the main material used in superstructure components of railway bridges. Hence, the effects of corrosion and fatigue are two of the most critical factors for the durability of a bridge.

The data shows that timber was used in the substructure and/or superstructure in less than 3% of railway bridges in this urban area of Australia. Therefore, although decay and termite attack were identified as critical factors for timber bridge deterioration, they were not very important for the above network of railway bridges which were located mainly in an urban area where timber was not considerably used. In addition, based on the decision made by that company and some other interviewed companies, timber will not be used in the future as either super or substructure. However, as timber has been widely used in remote areas, the factors associated with degrading timber components were taken into account as critical in this research. Figure 3-4 depicts the wide usage of concrete in substructures, therefore, the effects of temperature change, creep and shrinkage, corrosion of reinforcement, sulphate and aggregate reaction, chemical damage from carbonation and chlorides, etc. were important considerations for evaluating the degradation of many bridges.

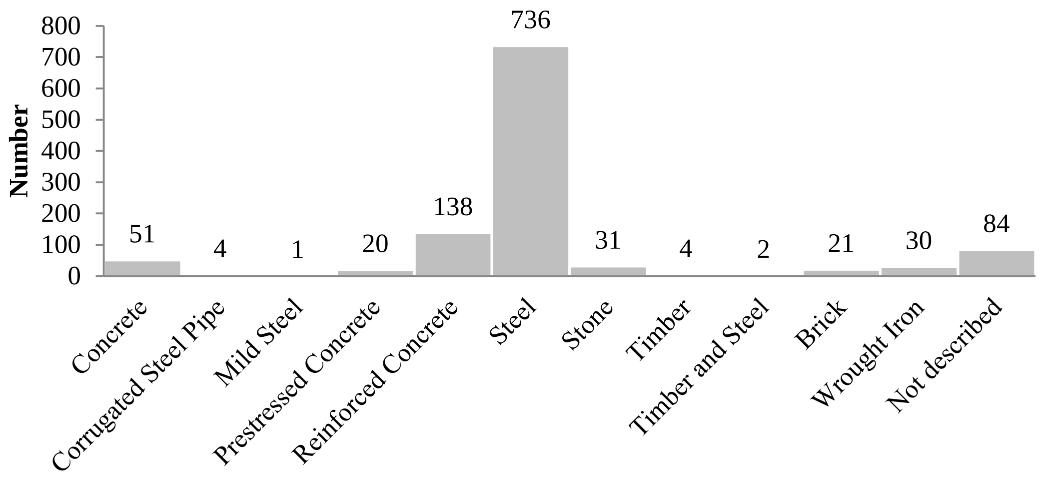

Figure 3-3 Material of superstructure of railway bridges

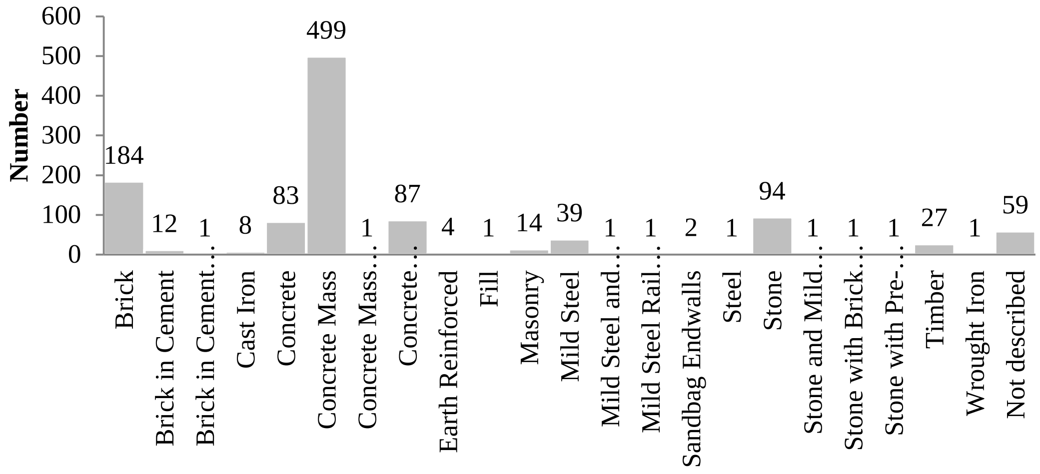

Figure 3-4 Substructure materials

Figure 3-4 also shows the wide usage of masonry materials such as brick, and stone in bridges and therefore the relevant factors involving the effects of ice and water, vibration, weathering, etc. were considered critical factors. Figure 3-5 shows the wide usage of spread foundations, therefore, the effect of flood on these structures should be significant. Figure 3-6 shows the materials of the foundation of these railway bridges, identified through the inspection process. It can be observed that the materials of about 45% of these railway bridges were not identified through inspection processes. Therefore, there were considerable uncertainties about the condition of the material of the foundation components, as the damage associated with them and the cause of such damage, which determines the importance of critical factors, could not be easily be identified.

Flood is another significant factor in degrading these structures. The average contribution of flood in degrading the condition of the concerned network of railway bridges in this study was 20% of the total bridge deterioration. Although reliable long time records related to earthquakes were not available in the studied database, interviews with the engineers and the risk assessment conducted through the earthquake design standard (AS1170.4, 2007) did not identify earthquake as an important factor. However, as seismic effect on a structure is significant in many parts of the world, and as this research aimed to develop a method that can be used globally, it was considered one of the critical factors in this thesis.

The probability of occurrence and severity of wind in cyclonic areas in Australia are high, hence, this factor was considered a critical factor in this research. According to this study, vehicular impacts of railway bridges that pass over roads should be taken into account as critical factors.

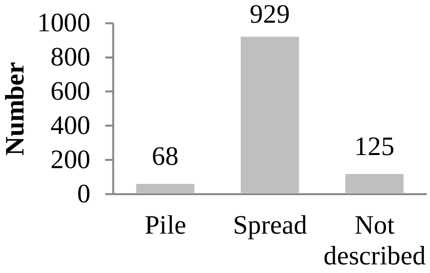

Figure 3-5 Foundation type

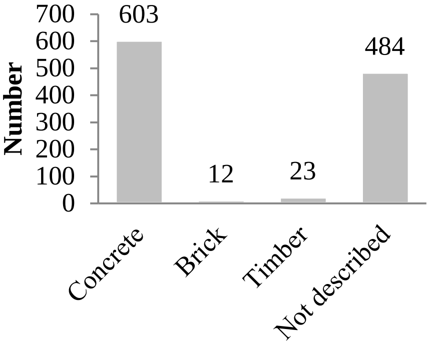

Figure 3-6 Foundation material

3.3.3 Quantification of Critical Factors

This section presents a method for estimating the importance and quantification of the critical factors used in Eq. 3.2. By estimating the importance of critical factors, the contribution of different critical factors towards bridge deterioration is evaluated. The method takes into account three restrictions: 1) availability and sufficiency of data in the database of BMS, 2) feasibility of the method for quantifying the importance of critical factors, and 3) capability of the method to be used for a network of railway bridges. According to this method, first, the average importance of each critical factor for a network of railway bridges is identified. Then for each bridge the coefficients (e.g. C_{ev}, C_{fl}, C_w, C_{eq}, and C_{col}), which show the risk of occurrence and severity of each critical factor are calculated. Finally the AHP method is used to synthesize the risk of all critical factors and produce the overall importance of critical factors (e.g. $\alpha_{fl}, \alpha_{w}, \alpha_{e}, \alpha_{col}, \beta_{ev}$).

In this section, only the risks associated with the severity and probability of occurrence of different critical factors are taken into account. Later, when the criticality and vulnerability of the components are evaluated, the effect of each critical factor on the structure is considered.

3.3.3.1 Average Importance of Critical Factors at the Network Level

To identify the average importance of critical factors at a network level, the opinions of experts in a company managing 1122 railway bridges in Australia, were collected by conducting a survey and interviewing them. Table 3-1 shows the results of the survey. These experts took into account the average proportion of invested repair costs associated with each of the critical factors within a different specific period for each of them. The estimation is approximate. The survey was required due to the lack of information in the BMS database. This information can be used as a starting point; however, more reliable data is needed to be collected in future, by inspecting and recording the cause of defects due to each of the identified critical factors, and the amount of resources invested to repair them. Therefore, based on the cost invested to repair each defect and by knowing the critical factor associated with that defect, the contribution of each factor towards bridge deterioration will be identified overtime. The reason for the unavailability of the above data is that the current BMSs have not been designed based on the rating method proposed in this thesis. This recommendation assists in providing relevant and sufficient data through inspection, which is required for the proposed rating method. Table 3-1 can be reproduced for any other network of bridges.

Table 3-1 The average importance of each critical factor for a network of railway bridges

Critical Factors	Estimation of the repair cost as a percentage
Flood/Scour	20%
Wind	0.1%
Earthquake	0.1%
Collision	5%
Environmental and fatigue	74.8%

The figures mentioned in Table 3-1 are not constant for every bridge. They will change based on the location of the bridge and environmental conditions. Therefore, the importance of critical factors should be calculated for each individual bridge. To this purpose, the coefficients related to each bridge are introduced and quantified as follows.

3.3.3.2 Criticality Coefficients of a Bridge

Coefficients, C_{ev}, C_{fl}, C_w, C_{eq}, and C_{col} respectively represent the severity and probability of occurrence of environmental effects, flood, wind, earthquake and collision in the region where the bridge is located. In order to quantify them, the risk assessment procedures in the relevant Australian Standards such as AS1170.2 (2002), AS1170.4 (2007), AS5100.2 (2004) are used. The Australian standards were used in this research to illustrate the proposed method in this section e.g. Section 3.3.3 and its subsections. In any country that has structural design standards, similar risk assessment procedures should be available; therefore, the usage of the method is universal. Through the use of such risk assessment procedures in the design standards, valuable knowledge that is currently available is used to increase the reliability of this method without too much effort.

3.3.3.2.1 ENVIRONMENT COEFFICIENT

To quantify environment coefficient C_{ev}, the effects of the environment on different types of materials are considered. The four environmental categories and the environment coefficient C_{ev} associated with them are shown in Table 3-2. In order to assign a single value (C_{ev}), from Table 3-2 to a bridge, the average effect of environment on different materials of the components of the bridge is taken into account. By recording the cause of future defects such as corrosion, wear, temperature changes, termite attacks, etc., in the database of BMS, C_{ev} can be more accurately calculated for each of the different environmental factors. The figures mentioned in Table 3-2 are similar to the ones used in some of the current BMSs in Australia.

Table 3-2 Coefficient C_{ev} associated with the environmental condition of the bridge location

Environmental condition of the bridge location	C_{ev}
Very high deterioration	2.0
High deterioration	1.5
Medium deterioration	1.0
Low deterioration	0.5

3.3.3.2.2 FLOOD COEFFICIENT

The flood coefficient C_{fl} , shows the severity and probability of the occurrence of a severe flood in the area where the bridge is located. The Average Return Interval (ARI) is taken into account to calculate C_{fl} . According to AS 5100.2 (2004), the bridge should not collapse due to any flood with average return interval of 2000 years. If the critical design condition takes place at an average return interval of less than 2000 years, a load factor (γ_{WF}) should be applied based on AS 5100.2 (2004). Figure 3-7 shows the relationship between ARI and the load factor. Here this load factor is considered as the criticality of flood (C_{fl}) and it is equal to the ultimate load factors (γ_{WF}) introduced in AS 5100.2 (2004). According to this standard (e.g. (AS5100.2, 2004)), C_{fl} (γ_{WF}) will be calculated using Eq. 3.4.

$$C_{fl} = 2 - 0.5\log(\frac{ARI}{20}) \qquad 3.4$$

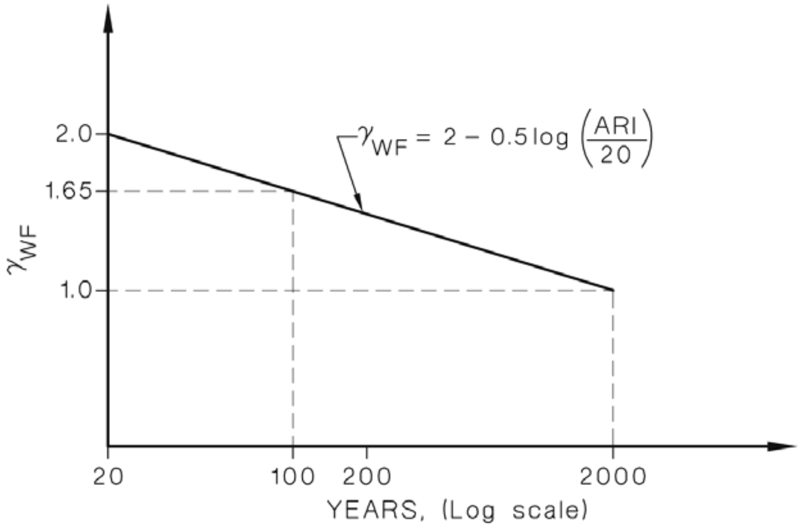

Figure 3-7 The relationship between the load factor and the flood average return interval, used for critical design condition AS 5100.2 (2004)

If the railway bridge is located in a place where there is no possibility for flood, this coefficient can be considered as zero. However, to avoid possible errors that could arise when a number is divided by zero in the creation of the pair-wise matrix *A* that will be explained in Section 3.3.3.3, a very small number e.g. 0.0001 can be assumed instead. If not, the column and row associated with flood in that matrix needs to be eliminated.

3.3.3.2.3 WIND COEFFICIENT

To calculate the effect of wind load on the structure, factors such as region, wind direction, terrain/height, shielding, and topography should be considered. However, because in this section only the risk associated with the severity and probability of occurrence of wind was taken into account, only the risk related to the bridge region was considered. Other parameters mentioned above, are taken into account when the effect of wind load on the structure is calculated in Section 3.4.5. Figure 3-8 shows different wind regions in Australia according to AS 1170.2 (2002).

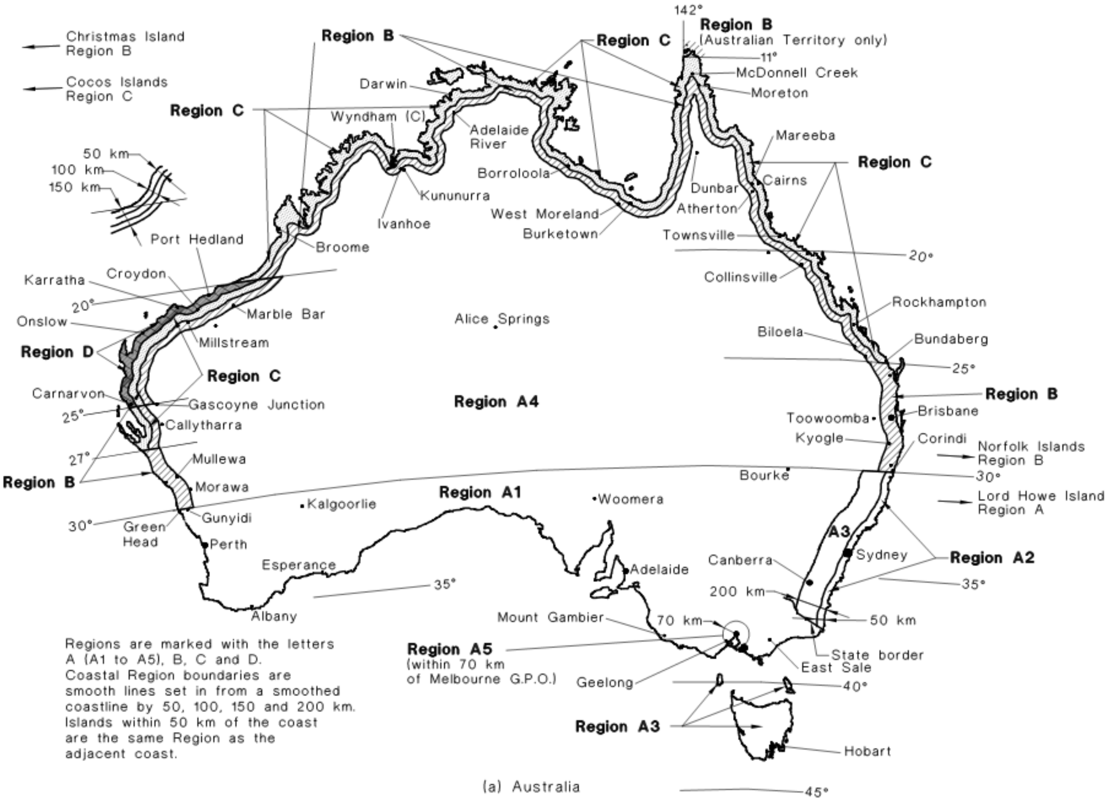

Figure 3-8 Wind regions (AS 1170.2 2012)

The regional wind speed of the average recurrence interval 2000 years (V_{2000}) is considered to calculate C_w. The values of V_{2000} can be obtained from AS 1170.2 (2002) for different regions. The calculated values of coefficient C_w by using Eq. 3.5 are shown in Table 3-3. Region W in Table 3-3 is located in a New Zealand wind regions map which can be found in AS 1170.2 (2002).

$$C_w = \frac{V_{2000} \text{ of the region where the bridge is located}}{V_{2000} \text{ of the region A}} \quad 3.5$$

Table 3-3 Coefficient C_w associated with the wind load of the bridge location

Location of the Bridge	C_w
Region A	1
Region W	1.23
Region B	1.31
Region C	1.60
Region D	2.06

3.3.3.2.4 EARTHQUAKE COEFFICIENT

To calculate the hazard associated with earthquake C_{eq}, parameters including site hazard (Z) and probability factor K_p from AS 1170.4 (2007) were taken into account. Figure 3-9 shows the earthquake hazard map of Australia (AS1170.4, 2007). Eq. 3.6 can represent the criticality of the earthquake factor for the structure based on the calculation of horizontal equivalent static shear force acting at the base of the structure as follows.

$$C_{eq} = 10K_pZ \tag{3.6}$$

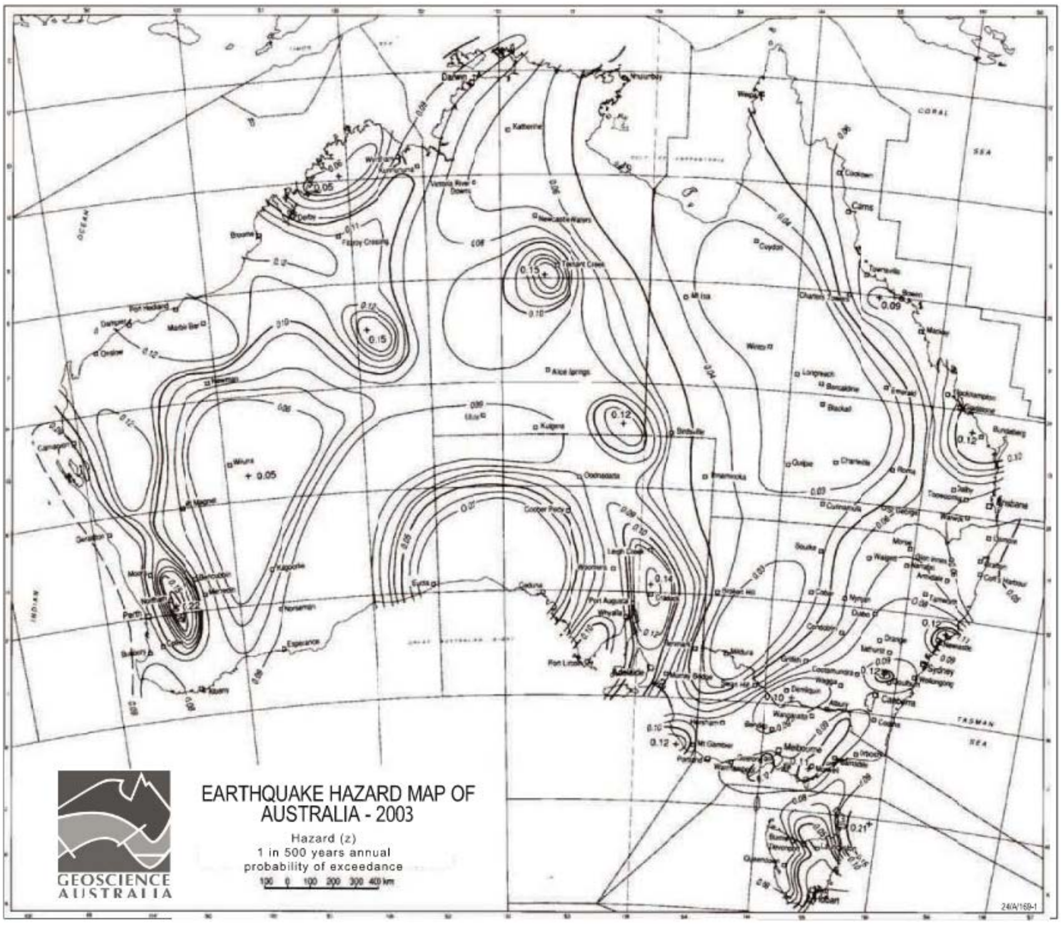

Figure 3-9 Earthquake hazard map of Australia (AS1170.4, 2007)

3.3.3.2.5 COLLISION COEFFICIENT

Coefficient C_{col} is obtained from Table 3-4 and based on the volume of the road traffic. If the incidents of vehicular impacts and the severity of damages associated with them are recorded in the process of bridge inspection, the suggested values in Table 3-4 can be more reliably calculated in future. If the railway bridge is not passing over a road, or its components are protected from vehicular impacts, this coefficient will be considered as zero. However, to avoid errors in the creation of the pair-wise matrix *A* (explained in Section 3.3.3.3), due to dividing a number by zero, a very small number e.g. 0.0001 can be assumed instead. If not, the column and row associated with collision in that matrix need to be removed.

Table 3-4 Coefficient C_{col} associated with the probability of the collision impacts

Traffic volume of road pass under the railway bridge	C_{col}
High Traffic	1.25
Medium Traffic	1.0
Low Traffic	0.75

3.3.3.3 Overall Importance of Critical Factors of a Bridge

In order to identify the overall priorities of different critical factors the AHP method was used in this research. The advantages of AHP as explained in Section 2.2.3.2, was the reason that the AHP was identified as the best method for prioritising the critical factors. AHP has several layers. The first layer is the goal (objective). The next level encompasses criteria that are related to the quality of the decisions. These criteria may be split into more detailed layers, called indices. The number of levels depends on the required accuracy and complexity of the problem (Zahedi, 1986; Saaty, 1990; Sasmal and Ramanjaneyulu, 2008).

Assigning weights or importance factor to the elements of each level is the next step after constructing the hierarchy structure. The comparative levels form a pair wise matrix (as shown in Matrix B e.g. Eqs. 3.7 and 3.8) to compare different elements. At this level, eigenvalue calculations (Eq. 3.9) are used to estimate the relative weights of the decision alternatives associated with each criterion. Synthesizing the weights to indicate the relative weighting factors for each alternative is the last step (Harker and Vargas, 1987; Triantaphyllou et al., 1997; Sasmal and Ramanjaneyulu, 2008).

Comparison Matrix **B** (Sasmal and Ramanjaneyulu, 2008)

$$B = \left[b_{ij} \right] = \left[\frac{w_i}{w_j} \right] \tag{3.8}$$

$$\mathrm{B} = \begin{bmatrix} 1 & b_{12} & b_{13} & \dots & \dots & \dots & b_{1m} \\ b_{21} & 1 & b_{23} & \dots & \dots & \dots & b_{2m} \\ b_{31} & b_{32} & 1 & \dots & \dots & \dots & b_{3m} \\ \vdots & \dots & \dots & \dots & \dots & \dots & \vdots \\ \vdots & \dots & \dots & \dots & b_{ij} & \dots & \vdots \\ \vdots & \dots & \dots & \dots & \dots & \dots & \vdots \\ b_{m1} & b_{m2} & b_{m3} & \dots & \dots & \dots & 1 \end{bmatrix} \tag{3.7}$$

$$BW = \lambda_{\max} W \tag{3.9}$$

- $\mathrm{w_i}$, $\mathrm{w_j}$ are the weight of each item
- $\lambda_{\max}$ is the maximum eigenvalue and W is the principal eigenvector of matrix B

The consistency of the matrix B can be calculated by Eqs. 3.10 and 3.11.

$$\mathrm{CR} = \frac{\mathrm{CI}}{\mathrm{RCI}} \tag{3.10}$$

$$\mathrm{CI} = (\lambda_{\max} - \mathrm{n})/(\mathrm{n} - 1) \tag{3.11}$$

RCI is Random Consistency Index. Saaty (Saaty, 1994) proposed RCI (shown in Table 3-5), and it is an average random consistency index calculated from a sample of 500 randomly produced matrices. CR is the consistency ratio that should be less than 0.1.

Table 3-5 RCI values of sets of different order ‘n’ adopted from (Saaty, 1994)

n	1	2	3	4	5	6	7	8	9
RCI	0	0	0.52	0.89	1.11	1.25	1.35	1.40	1.45

As explained above, first a pair-wise matrix is created in AHP. The entries of this matrix show the comparison between each pair of factors. In this thesis, matrix A (Eq. 3.12) shows the pair-wise comparison between critical factors. The eigenvector associated with the maximum eigenvalue represents the overall priority of the factors. The consistency of the pair-wise matrix can be calculated by Eqs. 3.10 and 3.11 and Table 3-5, as explained above.

In matrix A, environmental effects (Ev), collision (Col), flood (Fl), wind (W) and earthquake (Eq) were introduced as critical factors. The introduced equations for calculating each of the entries of matrix A are shown in Table 3-6. The numerical values in each equation of the entries A_{ij} of the matrix A are obtained from Table 3-1. For instance, the coefficient 14.96 used for calculating A_{12} is obtained from Table 3-1 by dividing the average criticality of environment by the average criticality of collision.

$$A = \begin{array}{c} \\ Ev \\ Col \\ Fl \\ W \\ Eq \end{array} \begin{array}{c} \begin{array}{ccccc} Ev & Col & Fl & W & Eq \end{array} \\ \begin{bmatrix} 1 & A_{12} & A_{13} & A_{14} & A_{15} \\ A_{21} & 1 & A_{23} & A_{24} & A_{25} \\ A_{31} & A_{32} & 1 & A_{34} & A_{35} \\ A_{41} & A_{42} & A_{43} & 1 & A_{45} \\ A_{51} & A_{52} & A_{53} & A_{54} & 1 \end{bmatrix} \end{array} \qquad 3.12$$

Table 3-6 Equations for calculating the entries of matrix A

$A_{ii} = 1$	$A_{ij} = \dfrac{1}{A_{ji}}$
$A_{12} = 14.96 \dfrac{C_{ev}}{C_{col}} C_{m1}$	$A_{13} = 3.74 \dfrac{C_{ev}}{C_{fl}} C_{m2}$
$A_{14} = 748 \dfrac{C_{ev}}{C_{w}} C_{m3}$	$A_{15} = 748 \dfrac{C_{ev}}{C_{eq}} C_{m4}$
$A_{23} = 0.25 \dfrac{C_{col}}{C_{fl}} C_{m5}$	$A_{24} = 50 \dfrac{C_{col}}{C_{w}} C_{m6}$
$A_{25} = 50 \dfrac{C_{col}}{C_{eq}} C_{m7}$	$A_{34} = 200 \dfrac{C_{fl}}{C_{w}} C_{m8}$
$A_{35} = 200 \dfrac{C_{fl}}{C_{eq}} C_{m9}$	$A_{45} = 1.0 \dfrac{C_{w}}{C_{eq}} C_{m10}$

The coefficients C_{m1} to C_{m10} represent the comparisons between two factors, which can be suggested by engineers for each individual bridge. Their default values are 1.0. According to the proposed method, these coefficients are not required to be introduced unless the engineers or managers intend to take into account special measures in an unpredictable situation. In fact, the only reason for introducing the coefficients C_{m1} to C_{m10} is to allow “human” control in the decision-making process. An example of applying the preceding coefficients would be for a higher possibility of collision in a specific bridge being considered based on deficiency in the design of the road passing under the bridge. In this case, $C_{m1}, C_{m5}, C_{m6},$ and C_{m7} would be considered by engineers. Another example is the case that a higher risk of flood should be considered for a particular bridge because of changes in the topography in the riverbed. In this case engineers might estimate the increased risk of the inundation of the superstructure during the flood, and assign appropriate values to $C_{m2}, C_{m5}, C_{m8},$ and C_{m9}. The preceding values would be calculated based on changes to the risk of inundation before and after significant changes in the riverbed topography. For particular cases, such as those mentioned above, the engineer might estimate the increase or decrease in risk with respect to normal conditions and calculate an appropriate C_{mi} coefficient. By adopting AHP, the experts’ and managers’ opinions, as well as the company practices and culture, can be incorporated into the decision-making process. The absolute value of eigenvector associated with the maximum eigenvalue of the matrix A will provide the values for coefficients, $\alpha_{fl}, \alpha_{w}, \alpha_{e}, \alpha_{col}$, and β_{ev}.

3.3.3.4 Illustrative Example

The proposed method is illustrated through its application to three railway bridges under different environmental conditions and different levels of risk associated with different extreme events. Table 3-7 shows the importance of critical factors towards the deterioration of the three bridges considered. Table 3-8 shows the calculated coefficients, $C_{ev}, C_{fl}, C_{w}, C_{eq}$ and C_{col}, for the three bridges.

Assuming that engineers and managers are not required to make any special considerations, all C_{m1} to C_{m10} will be equal to 1.0. After calculating all of the entries of the pair-wise matrices *A1*, *A2*, and *A3* from Table 3-6, the matrices *A1*, *A2*, and *A3* will be determined. The maximum eigenvalue (λmax) for the matrix *A1* is calculated as 5.00, and the consistency ratio of the matrix *A1* (CR) can be investigated through Eqs. 3.10 and 3.11. CR related to matrix *A1* is equal to 0.00, which is less than 0.1. The consistencies of the other two matrices will also be investigated in the same way.

Table 3-7 The risk associated with the critical factors of the three railway bridges

	Environmental Condition	Flood (ARI)	Wind Region	Earthquake Hazard (z)	Earthquake Probability Factor (K_p)	Traffic Volume
Bridge 1	High deterioration	100	B	0.1	1.5	Medium
Bridge 2	Low deterioration	20	A	0.05	1.5	Low
Bridge 3	High deterioration	No Flood Risk	B	0.1	1.5	Medium

The eigenvectors of the *A1*, *A2*, and *A3* matrices related to the three bridges which show the importance of critical factors of these bridges are calculated and shown in Table 3-9. As can be observed from Table 3-9 the average importance of critical factors shown in Table 3-1 can change dramatically due to the location of the bridge and changes in the risk of probability of occurrence or the severity of extreme events. For instance, for the second bridge, when the risk associated with environmental effects is low, while that associated with flood is quite high, the contribution of the flood towards bridge deterioration will be even higher than environmental effects, and more than twice of the average risk for flood shown in Table 3-1. For bridge 3, the effect of environmental factors towards bridge deterioration will be about 95%, when the risk related to flood is almost zero.

Table 3-8 Calculation of the coefficients

Coefficients	Bridge 1	Bridge 2	Bridge 3
C_{ev}	1.5	0.5	1.5
C_{col}	1	0.75	1
C_{fl}	1.65	2	0.0
C_w	1.31	1	1.31
C_{eq}	1.5	0.75	1.5

$$A1 = \begin{bmatrix} 1 & 22.44 & 3.4 & 856.4885 & 748 \\ 0.0446 & 1 & 0.1515 & 38.1679 & 33.3333 \\ 0.2941 & 6.6 & 1 & 251.9084 & 220 \\ 0.0012 & 0.0262 & 0.0040 & 1 & 0.8733 \\ 0.0013 & 0.03 & 0.0045 & 1.1450 & 1 \end{bmatrix}$$

$$A2 = \begin{bmatrix} 1 & 9.9733 & 0.935 & 374 & 498.6667 \\ 0.1003 & 1 & 0.0938 & 37.5 & 50 \\ 1.0695 & 10.6667 & 1 & 400 & 533.3333 \\ 0.0027 & 0.0267 & 0.0025 & 1 & 1.3333 \\ 0.0020 & 0.02 & 0.0019 & 0.75 & 1 \end{bmatrix}$$

$$A3 = \begin{bmatrix} 1 & 22.44 & 856.4885 & 748 \\ 0.0446 & 1 & 38.1679 & 33.3333 \\ 0.0012 & 0.0262 & 1 & 0.8733 \\ 0.0013 & 0.03 & 1.1450 & 1 \end{bmatrix}$$

Table 3-9 The importance of critical factors (e.g. contribution of the critical factors towards bridge deterioration)

Contribution of Factors	**Bridge 1**	**Bridge 2**	**Bridge 3**
β_{ev}	0.958465	0.681371	0.999007
α_{col}	0.042712	0.068319	0.044519
α_{fl}	0.281989	0.728739	0.0
α_{w}	0.001119	0.001822	0.001166
α_{e}	0.001281	0.001366	0.001336

From the above calculations, it can be observed that by determining only six simple data (e.g. environmental condition, flood (ARI), wind region, earthquake hazard (Z), earthquake probability factor (K_p), traffic volume) as shown in Table 3-7, the importance of each critical factor can be identified. Hence, the proposed method is practical and can be used to identify the importance of critical factors for each individual bridge in a network of thousands of bridges. The rating method based on the outputs of the method mentioned here will be more reliable, as it uses the risk assessment procedures available in current design standards. The method can assist engineers and managers in the decision-making process by utilizing the AHP.

3.4 QUANTIFICATION OF WEIGHTING FACTORS

This section outlines the quantification of the weighting factors of components. The weighting factors show the criticality and vulnerability of the components related to different critical factors at the time of conducting structural analysis on the bridge.

Parameters $al_i, afl_i, aw_i, ae_i, acol_i$ of Eqs. 3.1 and 3.2, are the weighting factors assigned to each component of the bridge and they are respectively associated with live, flood, wind, earthquake and collision loads. As mentioned earlier, the methods for condition assessment of bridges are either practical enough to be applied to a network of bridges but not reliable, or reliable but not practical enough to be applied to a network of bridges. Currently adopted practical methods cannot answer the key question of whether the capacity of a current bridge is adequate to carry different loads. This is because they do not take into account the geometry of different structures of bridges, and the vulnerability of different components to different types of loads. Therefore, conducting structural analysis to identify weighting factors, which reflect the criticality of components for the structure and vulnerability of the components to critical factors, will be inevitable. However, this analytical method should be simple; otherwise, it would not be practical enough to be applied to a network of thousands of railway bridges. Vulnerability is defined by many researchers such as Lind (1995) and Suna et al. (2010) and in different performance based guidelines and research such as by FEMA P-420 (2009), and Augusti and Ciampoli (2008). In this thesis, the vulnerability of the components refers to the probability and consequence of the failure of each component due to the environmental effects, flood, wind, earthquake and collision.

To reduce the consumption of resources, including expertise, time and equipment, the structural analyses procedure should be simple, in a way that can be performed by a junior engineer with limited supervision by a senior engineer. Frequently performing structural analysis on thousands of bridges is not practical; as a result, it has been identified that the structural analysis and the reassessment of the weighting factors can be conducted every 20 years, or when the structural condition exceeds some specific safety or serviceability thresholds. The 20 years limit is an ultimate limit and each BMS can determine different values for that based on the deterioration rate of its bridges or the availability of its resources. The thresholds are discussed in the Section 3.5 and are determined based on the overall condition of the bridge and its load carrying capacities. It is very rare that the condition of a bridge deteriorates due to damage in more than a few critical locations, because prior to this condition the damaged components are identified and repaired and the overall condition of the bridge continually improved. According to the discussion in Section 3.5, the first decision is made based on the condition of the bridge component, and its load carrying capacity at the time of inspection. The majority of the railway bridges at the network level are simple structures with low levels of redundancies. Therefore, conducting alternative load path analysis to calculate the weighting factors do not significantly improve the reliability of the condition assessment of the bridge. Hence, these types of analyses can be avoided for the sake of simplicity. Sophisticated analyses similar to the method introduced by Wong (2006) or Xu et al. (2009) may only be performed for special bridges, which have a large number of degrees of freedoms or are significant or critical structures at the network level. The number of these types of bridges is limited, and as mentioned in the introduction, the study of them is outside of the scope of this research.

Considering the above explanations on the practicality of the analytical methods for determining the weighting factors, the calculation of the Demand by Capacity (D/C) ratios of the structural components of the bridge are introduced. At the safety level and for linear analysis, the demand refers to the internal stresses developed in components due to loads. The capacities of the different components are the combined strength capacities for carrying internal axial forces and moments and are calculated based on properties of the structural member, e.g. beams, columns, diaphragms, etc. For nonlinear analysis used to evaluate the vulnerability of the bridge to earthquake, the capacity of the components beyond their elastic limits can be taken into account.

SHM systems can also be used to measure the D/C ratios of components at both safety and serviceability levels. However, for practicality reasons, measurements need to be limited to the critical locations in a structure and its components, and some specific responses e.g. strain, deflection, and vibration. Demand at the safety level for each critical point of the critical component can be measured by measuring the strain in that point, and the capacity will be the yielding strain at that point. As a result of using SHM systems, the D/C ratios can be continually calculated and will be highly reliable, as the real demands at the time of applying loads are measured. However, at this stage of the bridge management system, SHM systems need to be applied to important bridges or bridges with very critical conditions, to reduce the cost of condition assessment. Taking into account the valuable advantages of the SHM system, including the real-time monitoring of the condition of the bridge and the reliability of its outcome, the recommendation will be made to install the sensors in the critical components of all new bridges to measure their D/C ratios.

At the serviceability level, the demand is the deflection or vibration of components due to the forces applied to them and the capacity refers to the allowable limits for deflection and vibration of components defined by design standards. Similar to the safety level, SHM outputs can be replaced with conducting structural analysis at the serviceability level as well. The SHM method will be a very strong tool to continuously measure the demands (e.g. deflections and vibrations) of each bridge component. The capacity of a component at the serviceability level is determined in the design standards as constant values. By using the SHM systems, as the real demand will be measured at any point in time, the criticality and vulnerability of the components at the serviceability level can be continually determined with a very high level of reliability.

The D/C calculations provide an appropriate understanding of the real performance of the railway bridges. Although due to bridge deterioration the components reduce their capacities, many of them can still safely carry loads, as safety factors larger than 1 are always adopted. Therefore, D/C ratios of components can reliably represent their criticality to carry live loads and their vulnerability towards critical factors. In this research, D/C ratios were used as weighting factors of the components.

Weighting factors should be calculated at both safety and serviceability levels. Here the components of a railway bridge are placed in three categories, including 1) structural components, 2) non-structural components and 3) structural details. At the safety level, the D/C ratios of the structural components are calculated at Ultimate Limit State (ULS), and considered weighting factors of the structural components. For non-structural components, consequences due to any failure in them should be investigated at the safety limit state to calculate weighting factors of each component associated with different critical factors. As an example, if a non-structural component such as the kerb is damaged, the ballast will not remain in its position and the whole system of damping and evenly distributed train loads on the superstructure will change. Therefore, although kerbs are not modelled in the design process, any changes in them can significantly change the assumptions that the structural engineers considered during the design of the structure. For structural details, their criticality should be identified based on what effect any changes in their condition may have on the performance of the structure in carrying load. For instance, any changes in structural details such as joints can change the initial boundary conditions of components and consequently the structural behaviour of the railway bridge.

At the Serviceability Limit State (SLS), changes in the condition of the structural components, non-structural components and structural details are taken into account to determine the criticality and vulnerability of the components. The criticality and vulnerability of the structural component is determined by using the SHM system, or it can be calculated separately by applying different loads including live load, flood, wind, and earthquake at SLS and calculating the D/C ratios. For non-structural components, and structural details, the consequences due to any damage in them or changes in their condition on the serviceability should be estimated. This estimation should be conducted by recording the cost associated with the malfunctioning of the bridge due to damage in a non-structural component, or a structural detail, in the long run. The criticality or vulnerability of the non-structural components and structural details is calculated based on the estimated consequences.

Condition assessment and rating of thousands of railway bridges with different ages, materials, structural configuration, etc. and assessing their vulnerability to different factors is enormously complex and requires vast resources and time to accomplish. Therefore, the subjectivity of these methods cannot be simply eliminated in a short period. One of the significant gaps found in the literature is that there is not a platform that is capable of using different investigations on bridge deterioration subjected to different factors such as the many different environmental factors. One of the advantages of the synthetic rating method compared to other current rating methods is that this method as a platform has significant potential for improvement. The improvements can be made by using the outcomes of any investigations on the effects of a critical factor, such as one of the many environmental factors on the structure, and introducing new weighting factors or enhancing the accuracy or reliability of the weightings and incorporating them into the synthetic rating equations (Eqs.3.1 - 3.3).

At this stage, because adequate investigations on the consequences of failure at both the safety and serviceability levels on non-structural components and structural details have not been conducted, the weighting factors used by BMSs such as VicRoads (Austroads, 2004) can be utilized for all critical factors. Every bridge authority can use the weighting factors of its own BMSs for this purpose. These weighting factors should be divided by the highest value of the weighting factors to scale them down to a number between 0 to 1, to match with other weighting factors obtained from D/C ratio analysis.

In order to illustrate how the weighting factors for non-structural components and structural details can be extracted from the BMSs of other countries, the New York method can be mentioned. For the New York method explained in Section 2.2.2.7 a weighting factor from 1 to 10 is assigned to each component including non-structural components and structural details. To use them as weighting factors they should be divided by 10 to be scaled down to a number from 0 to 1, to be comparable with the weighting factors of structural components calculated from their D/C ratios. Figure 3-10 shows the methods for calculating the weighing factors of the components and structural details for each critical factor.

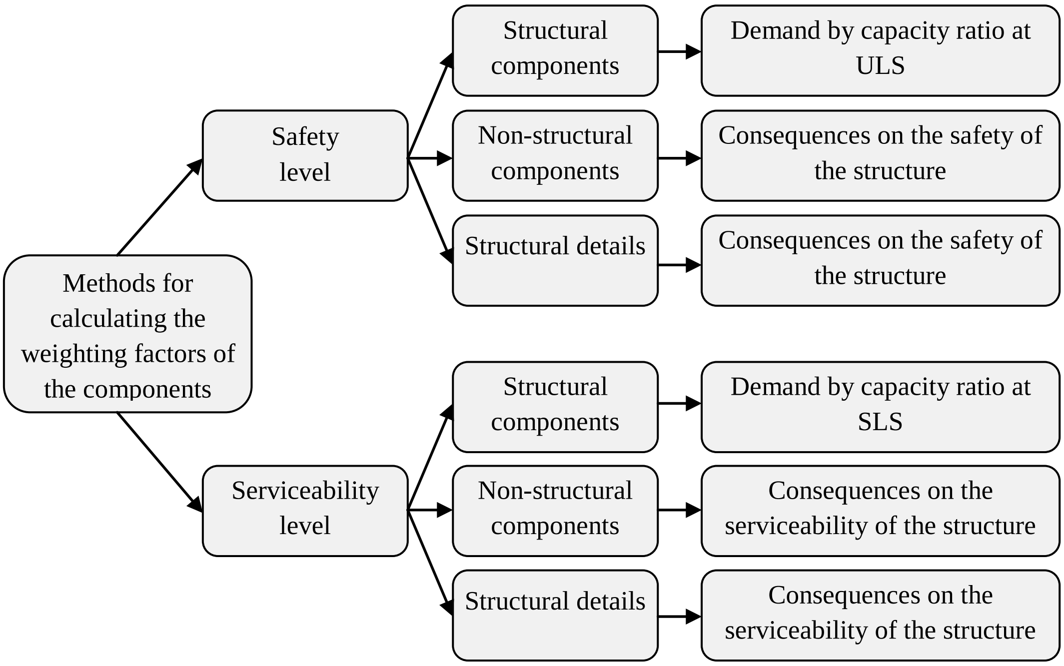

Figure 3-10 Methods for calculating the weighting factors of structural and non-structural components and structural details

As explained previously, for structural components, the D/C ratios (weighting factors) should be calculated both at safety and serviceability levels, to evaluate the behaviour of the bridge at both levels, but here only the safety level is explained, as the procedures for both are similar. The calculation of weighting factors is explained in more details as follows.

3.4.1 Live Load Weighting Factor

Live load is the most important load, as carrying live loads with an acceptable level of safety and serviceability are the main purposes of building a bridge. Making decisions about the condition of the components based only on the inspection reports is not appropriate. To calculate the weighting factors associated with live load (al_i), the D/C ratios of components when the structure is subjected to live load are calculated. In the design process, the capacities of the components are determined based on the type of forces applied to them. For instance, beams are designed for bending moments, while columns are designed for the combined effects of axial forces and bending moments.

To calculate the demand, the combination of dead and live load is taken into account. Instead of the live loads mentioned in the current standards, the maximum train loads, which are currently applied to each specific bridge in the network, are taken into account as the live loads. As the standard loads can be too conservative, they may identify those old bridges, which are capable of carrying the current real loads, as unsafe bridges. In other words, the real performance of the current structure and under current live loads should be taken into account. In order to calculate the capacity of the components, Australian standards such as AS 5100.5 (2004), AS 3600 (2009), AS 4100 (1998) etc., are used. Every country may use its own design codes, for instance in the United States AASHTO LRFD 2007 (2007), ACI 318-05/IBC2003 (2005) and AISC360-05/IBC2006 (2005) may be used. Only the Australian Standards are mentioned here as an example.

Safety factors, which will be applied within the design process and are related to the uncertainty of the characteristics of materials, methods of construction, etc., should still be taken into account. The D/C ratio of a component in the range of 0 to 1 means that at the time of calculating D/C ratios, the component can still carry loads. Higher D/C values show more criticality of the condition of the components. In order to calculate al_i , engineers should also take into account the susceptibility of the component to the increase of load by conducting dynamic analysis. Because of the importance of the effect of live load on the safety and serviceability of the bridge, detailed investigation was conducted on the dynamic effects of train load on the structure in Chapter 4 of this document. Chapter 4 shows that resonant vibration can have a significant impact on the D/C ratios of the components.

3.4.2 Flood Weighting Factor

In order to quantify the weighting factors of components associated with flood (afl_i) based on their D/C ratios, the combination of dead and flood loads is taken into account. According to AS 5100.2 (2004), the forces applied to the railway bridges due to a flood include drag forces on piers, lift forces on piers, drag force on the superstructure, lift force on the superstructure, moment on the superstructure, forces due to debris on sub and super structures, and forces due to log impact.

3.4.3 Collision Weighting Factor

Collision here refers to vehicle impact. Ship impact is not applicable to the types of railway bridges considered in this research. To calculate the D/C ratios of components associated with collision ($acol_i$), loads and their directions can be obtained from relevant standards. For instance in Australia the relevant standard is AS 5100.2 (2004). Through conducting structural analysis and design, if the protection beam or barriers are identified as capable of resisting the collision loads, the vulnerability assessment is not required.

3.4.4 Earthquake Weighting Factor

Earthquake is one of the critical factors in damaging railway bridges in many parts of the world and is important for the life cycle bridge management and estimating the cost of maintenance and repair in the long run. For an earthquake, in order to take into account the capacity of the components beyond their elastic limits, nonlinear static analysis (pushover) is suggested for calculating the weighting factors of components (ae_i). Pushover analysis is mainly conducted on the substructure. If nonlinear analysis is conducted, the D/C ratios should be calculated based on plastic deformation of the components, and utilizing performance based design documents. In most parts of Australia the hazard of earthquake is not high, therefore, standards such as AS 1170.4 (2007) and AS 5100.2 (2004) can be used for estimating earthquake effects on the structure.

3.4.5 Wind Weighting Factor

To calculate the D/C ratios of components related to wind (aw_i) and obtain weighting factors associated with them in Australia, AS 1170.2 (2002), and AS 5100.2

(2004) are taken into account. According to the above standards, the design wind speed is calculated based on the average return interval, geographical location, terrain category, shielding, and height above the ground. Transverse, longitudinal and vertical wind loads at both ULS and SLS are derived. The combination of dead and wind loads is applied to the structure.

3.4.6 Environment Weighting Factor

For environmental effects and fatigue, weighting factors assigned to live load (al_i) are used. Environmental factors include many different parameters, such as corrosion for steel structures, changes in temperature, termite attack for timber bridges, etc. Each of these factors degrades the structure in a different way and some are inter-related. Although the effect of fatigue is different with respect to environmental factors as it happens because of cyclic loads, fatigue also gradually degrades the structure over a long period of time.

It will be recommended that investigations be conducted on fatigue or even on each individual environmental factor, to calculate a separate set of weighting factors for each of them. These investigations should include experimental and analytical research, as well as statistical analysis on the data in the database. Lack of adequate investigations and statistical analysis on data related to different environmental factors and fatigue in current BMSs, and as a result utilizing not so reliable methods such as probabilistic methods for predicting the future condition of the components, are the reasons for using live load weighting factor for them.

3.5 SYNTHETIC RATING PROCEDURES

This section presents the Synthetic Rating Procedure (SRP) for railway bridges. SRP shows how the synthetic rating method is used to rate bridges. By using the synthetic rating equations e.g. Eqs. 3.1 - 3.3, the condition of the components and the condition of the bridge can be expressed in terms of numerical values. SRP is based on synthetic rating equations. Figure 3-11 illustrates the SRP. The outputs of SRP are the ratings of the bridge and it components within a network of railway bridges, and identifying the deadlines for taking action. The actions include inspection, repair and maintenance, and structural analysis. The rating of the bridge and each of its components in this chapter is respectively identified based on the criticality and vulnerability of the components and the bridge associated with each critical factor. As can be observed in Figure 3-11 for each component of a bridge, several ratings are identified and each represents its rating associated with one critical factor in a network of railway bridges. Similarly, the figure shows that for each bridge in a network, several ratings are calculated and each represents its rating to one critical factor. Therefore, contrary to current rating systems, SRP evaluates the condition of the bridge from different perspectives.

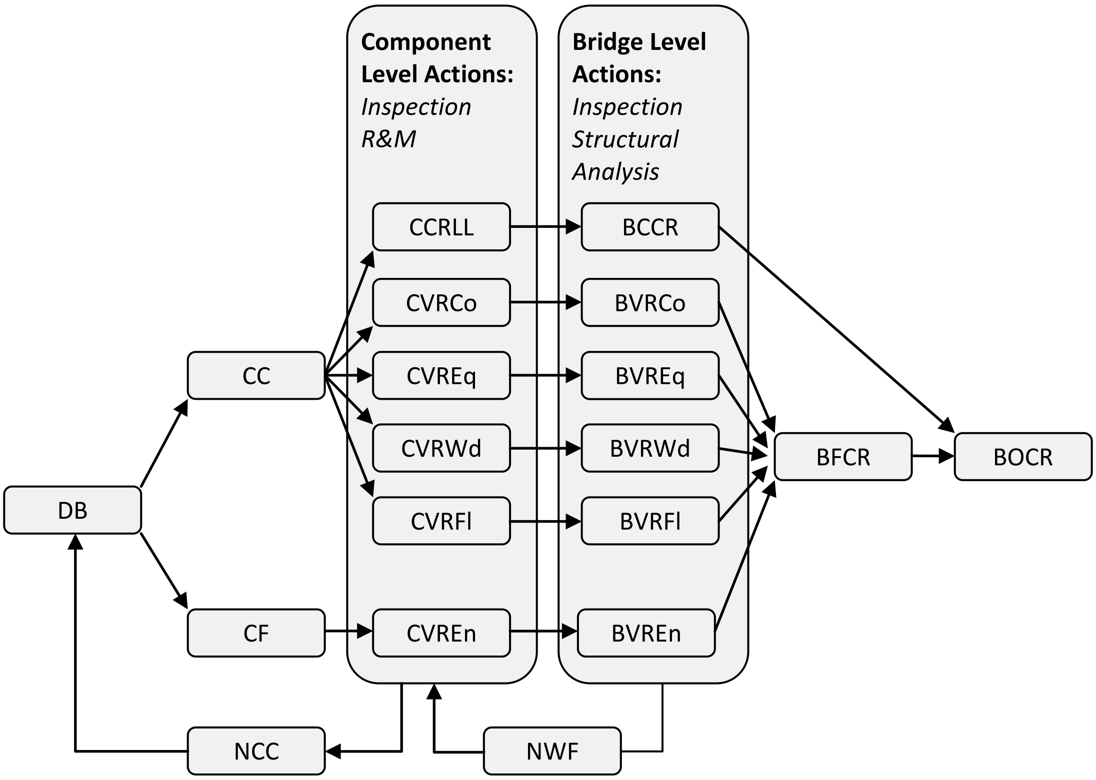

Figure 3-11 Flowchart of the synthetic rating procedure (SRP) for railway bridges

CF = C_{fi} , CC = C_{ci} , BCCR, BFCR, and BOCR as defined in Eqs. 3.1 - 3.3.

DB: Database of the BMS, which includes the inspection and inventory data

CVREn = $C_{fi}al_i$: Component *i* Vulnerability and Rating to Environment

CVRCo$_i$ = $C_{ci}acol_i$: Component *i* Vulnerability and Rating to Collision

CVREq$_i$ = $C_{ci}ae_i$: Component *i* Vulnerability and Rating to Earthquake

CVRWd$_i$ = $C_{ci}aw_i$: Component *i* Vulnerability and Rating to Wind

CVRFl$_i$ = $C_{ci}afl_i$: Component *i* Vulnerability and Rating to Flood

CCRLL$_i$ = $C_{ci}al_i$: Component *i* Criticality and Rating to Live Load

BVREn = $\frac{10}{n}\sum_{i=1}^{n} C_{fi}al_i$: Bridge Vulnerability and Rating to Environment

BVRCo = $\frac{10}{n}\sum_{i=1}^{n} C_{ci}acol_i$: Bridge Vulnerability and Rating to Collision

BVRWd=$\frac{10}{n}\sum_{i=1}^{n} C_{ci}aw_i$: Bridge Vulnerability and Rating to Wind

BVREq = $\frac{10}{n}\sum_{i=1}^{n} C_{ci}ae_i$: Bridge Vulnerability and Rating to Earthquake

BVRFl = $\frac{10}{n}\sum_{i=1}^{n} C_{ci}afl_i$: Bridge Vulnerability and Rating to Flood

NCC is the new component condition after repair, NWF is the new weighting factors for components after conducting structural analyses, and R&M denotes the repair and maintenance.

This section includes, 1) Assessing the current and future conditions of the components, 2) Criticality of the condition of the railway bridge subjected to live load, 3) Vulnerability of the railway bridge to critical factors, 4) Future condition of the railway bridges and their ratings in a network, and 5) Current and future conditions of the railway bridges and their ratings in network.

3.5.1 Assessing the Current and Future Condition of Components

This section outlines the criteria for assessing the current and future condition of the railway bridge and its components at the safety level. Although at the serviceability level the tables and limits are different from those that will be introduced in this section for the safety level, the method of defining them is almost the same.

According to SRP, assessing the condition of the bridge starts with inspection. At this stage, inspectors provide descriptive information on the condition of the components of the bridge. The current condition of the component (CInsp) can be estimated based on inspection reports and a number from 1 to 5 can be assigned to each component. Table 3-10 is used to calculate C_{ci} which is related to the current condition of the component *i*. Table 3-10 introduces 5 different conditions for the components of a railway bridge. In this table *LC* denotes the lost capacity of the structural components with respect to its intact condition. Intact condition refers to the condition of the component at the time of conducting the structural analysis. For example, condition 5 refers to the component that has lost more than 35% of its original capacity. Assigning levels 1 to 5 to different conditions and translating these numbers to *LC* facilitates the communication between engineers and managers. Other parameters of Table 3-10 were explained in the previous section.

The estimation of *LC* of components for the range of less than 10 percent is very difficult in practice. This is especially so as the visual inspection is considered the most common method for condition assessment and estimating the *LC* of components. In addition, writing descriptive information about the different conditions of the components that match with changes in capacities less than 10 percent would be very comprehensive and extremely difficult and costly. If inspectors use other methods to assess the condition of the components such as NDT or SHM, assigning a value to each component will be easier and more accurate.

The inspector is the person who can make a decision about the condition of the components at this first level and only about condition 5. If the condition of a component is five, it means the component should be immediately replaced. This will be the only decision that can be made at this stage. Because the criticality of the situation is not only related to the lost capacity at safety and serviceability states of the component, it is also related to the amount of force applied to the components and the consequences of any failure at safety and serviceability levels on the whole structure. As explained earlier, inspectors should have inspection manuals, which comprise descriptive information about each level mentioned in Table 3-10. For instance, for condition 2, the inspection manual should describe a component that has lost between 5 to 15 percent of its original capacity. The reliability of the method is dependent on these documents provided by experienced engineers and sufficient data in the database. Instead of developing descriptive documents by engineers and using those documents by inspectors in the way explained above, SHM systems can be adopted to evaluate the *LC* in a reliable way. The *LC* can be estimated by using SHM systems and by placing strain gauges in critical points of the bridge components to measure the strains at any time, and/or measuring the maximum deflection of the component using appropriate devices. For the safety level, the increase of strains in critical points of a component under the same load over time can show the *LC* of the components over time. For the serviceability level, the increase in the maximum deflection of a component under the same load over time can indicate the associated *LC*.

Table 3-10 Calculation of C_{ci} based on the condition assessment conducted by inspectors

Current condition of the components (CInsp)	**Description of the condition of the components**	$C_{ci} = 1/(1-(LC/100))\times 100$
1	$LC < 5\%$	$C_{ci} = 105$
2	$5\% \le LC < 15\%$	$C_{ci} = 118$
3	$15\% \le LC < 25\%$	$C_{ci} = 134$
4	$25\% \le LC < 35\%$	$C_{ci} = 154$
5	$35\% \le LC$	$C_{ci} = 182$

The future condition of the component can be predicted based on probabilistic processes such as the Markov Chain method (Agrawal et al., 2010). The future condition of each component (CMav), will be calculated by multiplying the transition probability matrix by the current condition of the component (e.g. 1 to 5) shown in Table 3-10. The future condition of the component is a number from 1 to 5 and is used in Table 3-21 to obtain C_{fi}. The calculation of the future condition of the components based on Markov Chain method was outside of the scope of this research and was carried out by other researchers involved in the main project (LCMRB) (Wellalage et al., 2013; Wellalage et al., 2014). As mentioned in the introduction chapter, LCMRB is about developing a Life Cycle Management for Railway Bridges and this research is a part of that. However, the criticality of the future condition of the components and bridge are discussed later in this thesis.

3.5.2 Criticality of the Condition of a Railway Bridge Subjected to Live Load

In this section, Table 3-11 is used to identify the criticality of each component of a bridge. The weighting factors of each component (al_i) is calculated as discussed in Sections 3.4 and 3.4.1. If the value of the weighting factor is between 0 to 1, this means that the component at the time of conducting structural analysis is capable of carrying the applied live load. By multiplying this value (al_i) to condition factors obtained from Table 3-10 (e.g. C_{ci}), the component criticality and rating to live load (CCRLL) can be determined. Table 3-11 shows the limits, and based on them, the criticality of the component for the whole bridge structure can be determined. The limits are similar to those mostly used in current BMSs. The compatibility of these tables to current practices facilitates their usage. By using the weighting factors that are determined based on structural analysis, or utilizing sensors, the subjectivity of the Table 3-11 and other similar tables related to the deadlines for taking action are significantly reduced in respect to the methods used in current practice. If the weighting factors are continually determined through SHM systems, the deadlines for taking action will be determined with high accuracy.

Table 3-11 Levels of criticality of components for carrying train load and deadlines for taking action

Level of the criticality	**Description of the criticality**	**Action to be taken**	
		Inspection	**Repair or Replacement**
Level CC1	CCRLL < 75	Regular (every 2 years)	Not required
Level CC2	75 ≤ CCRLL < 80	Within 1 year	Regular maintenance
Level CC3	80 ≤ CCRLL < 85	Within 6 months	Repair in 1year
Level CC4	85 ≤ CCRLL < 90	Within 3 months	Repair in 6 months
Level CC5	90 ≤ CCRLL	Bridge Closure	Immediately Replaced

At this stage, engineers can make decisions about the current condition of the component. In addition, engineers can compare different components of different bridges, and rate them accordingly. This will be the first stage of rating, which is the rating of the components of the bridges. Based on this number, engineers will identify the priority for action based on the structural condition of the component. If CCRLL is a number less than 100, it means that the component in its current condition (condition at the time of inspection), is capable of carrying the live load. According to Table 3-11, the levels from CC1 to CC5 are defined based on the different ranges of CCRLL. Levels CC1 to CC5 are descriptive information that will be used by experts who are specialists in different areas (e.g. management, financial, etc.), other than structural engineering. However, they have the responsibility of making decisions about allocating resources and prioritizing the repair or maintenance work. Table 3-11 also shows the deadlines for taking necessary action based on different ranges of CCRLL. For example, according to this table, for the level CC5 the component should be immediately replaced, and for lower levels the deadlines for conducting inspections and repair actions are identified.

The cost for improving the current condition of the selected railway bridges in the network with worst condition (Rcc) can be predicted based on Eq. 3.13. This prediction of cost is based on the cost that has been spent so far to improve the condition of the bridge. Eq. 3.13 takes into account the coefficient (γ_{1i}), which determines the amount of the budget allocated to improve the current condition of bridge *i*. The preceding coefficient for each bridge in the network identifies the rate of the bridge deterioration and considers the current and future rate of the bridge in the network, and is calculated using Eq. 3.22. All of the equations related to the prediction of costs e.g. Eqs. 3.13, 3.14, 3.15, 3.16, 3.17, 3.18, 3.19, and 3.20 are based on the historical data related to the cost associated with the different critical factors invested so far, to improve the condition of the bridge. The accurate cost should be calculated based on the final plans that will be provided after the prioritization level within the BMS and when the projects for the repair of each individual component are defined. At that level, all structural and non-structural factors are considered.

$$Rcc = \frac{\sum_{i=1}^{m} \gamma_{1i}}{m} \times TBcf \qquad 3.13$$

Where:

γ_{1i}: Coefficient used in Eq. 3.3, and it is associated with bridge *i* and will be calculated based on Eq.3.22.

$TBcf$: Total budget allocated to improve the current and future condition of the total railway bridges at the network level.

m : Total number of bridges in the network which need action.

The criticality of the condition of the railway bridge can be estimated through accumulating the criticality of the condition of the components (e.g. BCCR in Eq.3.1). Table 3-12 shows the different limits and the levels of criticality of the condition of the railway bridge to live load and the deadlines for taking action. In Table 3-12, more levels have been taken into account in respect to Table 3-11, to avoid unnecessary structural analyses.

Table 3-12 Levels of criticality of the current condition of a bridge for carrying train load and deadlines for taking action

Level of criticality	**Description of the criticality**	**Action to be taken**	
		Inspection	**Structural analyses**
Level BCCR1	BCCR <700	Regular (every 2 years)	within 20 years
Level BCCR2	700 ≤ BCCR < 750	Regular (every 2 years)	within 5 years
Level BCCR3	750 ≤ BCCR < 800	within 1 year	within 2 years
Level BCCR4	800 ≤ BCCR < 850	Within 6 months	within 1 year
Level BCCR5	850 ≤ BCCR < 900	Within 3 months	within 6 months
Level BCCR6	900 ≤ BCCR < 950	Within 1 months	within 3 months
Level BCCR7	950 ≤ BCCR	Immediate action	Immediate action

The budget assigned to each bridge (e.g. bridge *i*) associated with its current condition ($BBcc_i$) is predicted using Eq. 3.14:

$$BBcc_i = \frac{BCCR_i}{\sum_{j=1}^{m} BCCR_j} \times Rcc \qquad 3.14$$

Where:

BCCR: Explained in Figure 3-11

m : Total number of bridges in the network that action should be taken on them

3.5.3 Vulnerability of Railway Bridges

To predict the future condition of the railway bridge and its components, their vulnerability to flood, collision, earthquake, wind and environmental factors including the effect of fatigue are taken into account. For each extreme event, Table 3-10 is used to calculate C_{ci}. Tables similar to Table 3-11 and Table 3-12 are developed to define the level of vulnerability of the components and bridge. However, for each extreme event, the number of levels and the period for taking action will be different from Table 3-11 and Table 3-12, as bridges are not continuously subjected to extreme events.

The resources that should be allocated to improving the future condition of all railway bridges at the network level (Rfc) are predicted using Eq. 3.15.

$$Rfc = \frac{\sum_{i=1}^{m} \gamma_{2i}}{m} \times TBcf \qquad 3.15$$

Where:

γ_{2i} : Coefficient used in Eq.3.3, and it is associated with bridge i and will be calculated based on Eq. 3.21

$TBcf$: The same parameter used in Eq. 3.13

m : Total number of bridges in the network that action should be taken on them

3.5.3.1 Vulnerability of a Railway Bridge and its Components to Extreme Events

The levels of vulnerability of the components to extreme events including flood, wind, earthquake, and collision will be estimated based on Table 3-13, Table 3-14, Table 3-15, Table 3-16. In addition, based on these tables, the deadlines for taking action will be identified. As can be observed in the above tables, the period for taking action is assumed to be longer because severe extreme events do not frequently take place. If CVRFl is greater than 100 for one component, it means that when the structure is subjected to flood load and based on the condition of the component at the time of inspection, it will fail. The flood load refers to the load used to calculate the weighting factor of the component. The above conclusion can be made about other vulnerability values including CVRWd, CVREq, and CVRCo, respectively associated with wind, earthquake and collision.

Table 3-13 Levels of vulnerability of components to flood and deadlines for taking action

Level of Vulnerability	**Description of vulnerability**	**Action to be taken**	
		Inspection	**Repair or Replacement**
Level F1	CVRFl < 75	Regular (every 2 years)	Not required
Level F2	75 ≤ CVRFl < 80	Regular (every 2 years)	Regular maintenance
Level F3	80 ≤ CVRFl < 85	Within 1 year	Repair in 2 years
Level F4	85 ≤ CVRFl < 90	Within 6 months	Repair in 1 year
Level F5	90 ≤ CVRFl	Within 3 months	Repair in 6 months

Table 3-14 Levels of vulnerability of components to wind and deadlines for taking action

Level of Vulnerability	**Description of vulnerability**	**Action to be taken**	
		Inspection	**Repair or Replacement**
Level W1	CVRWd < 75	Regular (every 2 years)	Not required
Level W2	75 ≤ CVRWd < 80	Regular (every 2 years)	Regular maintenance
Level W3	80 ≤ CVRWd < 85	Within 1 year	Repair in 2 years
Level W4	85 ≤ CVRWd < 90	Within 6 months	Repair in 1 year
Level W5	90 ≤ CVRWd	Within 3 months	Repair in 6 months

Table 3-15 Levels of vulnerability of components to earthquake and deadlines for taking action

Level of Vulnerability	**Description of vulnerability**	**Action to be taken**	
		Inspection	**Repair or Replacement**
Level E1	CVREq < 75	Regular (every 2 years)	Not required
Level E2	75 ≤ CVREq < 80	Regular (every 2 years)	Regular maintenance
Level E3	80 ≤ CVREq < 85	Within 1 year	Repair in 2 years
Level E4	85 ≤ CVREq < 90	Within 6 months	Repair in 1 year
Level E5	90 ≤ CVREq	Within 3 months	Repair in 6 months

Table 3-16 Levels of vulnerability of components to collision and deadlines for taking action

Level of Vulnerability	**Description of vulnerability**	**Action to be taken**	
		Inspection	**Repair or Replacement**
Level CO1	CVRCo < 75	Regular (every 2 years)	Not required
Level CO2	75 ≤ CVRCo < 80	Regular (every 2 years)	Regular maintenance
Level CO3	80 ≤ CVRCo < 85	Within 1 year	Repair in 2 years
Level CO4	85 ≤ CVRCo < 90	Within 6 months	Repair in 1 year
Level CO5	90 ≤ CVRCo	Within 3 months	Repair in 6 months

The limits shown in Table 3-17, Table 3-18, Table 3-19, and Table 3-20, depict the vulnerability of the railway bridge to flood, wind, earthquake, and collision, and the deadlines for taking action for inspection and structural analysis.

Table 3-17 Levels of vulnerability of a bridge to flood load and deadlines for taking action

Level of vulnerability	**Description of vulnerability**	**Action to be taken**	
		Inspection	**Structural analyses**
Level BF1	BVRFl < 750	Regular (every 2 years)	within 20 years
Level BF2	750 ≤ BVRFl < 800	Regular (every 2 years)	within 5 years
Level BF3	800 ≤ BVRFl < 850	within 1 year	within 2 years
Level BF4	850 ≤ BVRFl < 900	Within 6 months	within 1 year
Level BF5	900 ≤ BVRFl	Within 1 month	within 3 months

Table 3-18 Levels of vulnerability of a bridge to wind load and deadlines for taking action

Level of vulnerability	**Description of vulnerability**	**Action to be taken**	
		Inspection	**Structural analyses**
Level BW1	BVRWd < 750	Regular (every 2 years)	within 20 years
Level BW2	750 ≤ BVRWd < 800	Regular (every 2 years)	within 5 years
Level BW3	800 ≤ BVRWd < 850	within 1 year	within 2 years
Level BW4	850 ≤ BVRWd < 900	Within 6 months	within 1 year
Level BW5	900 ≤ BVRWd	Within 1 month	within 3 months

Table 3-19 Levels of vulnerability of a bridge to earthquake load and deadlines for taking action

Level of vulnerability	**Description of vulnerability**	**Action to be taken**	
		Inspection	**Structural analyses**
Level BE1	BVREq < 750	Regular (every 2 years)	within 20 years
Level BE2	750 ≤ BVREq < 800	Regular (every 2 years)	within 5 years
Level BE3	800 ≤ BVREq < 850	within 1 year	within 2 years
Level BE4	850 ≤ BVREq < 900	Within 6 months	within 1 year
Level BE5	900 ≤ BVREq	Within 1 month	within 3 months

Table 3-20 Levels of vulnerability of a bridge to collision load and deadlines for taking action

Level of vulnerability	**Description of vulnerability**	**Action to be taken**	
		Inspection	**Structural analyses**
Level BCO1	BVRCo < 750	Regular (every 2 years)	within 20 years
Level BCO2	750 ≤ BVRCo < 800	Regular (every 2 years)	within 5 years
Level BCO3	800 ≤ BVRCo < 850	within 1 year	within 2 years
Level BCO4	850 ≤ BVRCo < 900	Within 6 months	within 1 year
Level BCO5	900 ≤ BVRCo	Within 1 month	within 3 months

The budget assigned to each bridge (e.g. bridge *i*) associated with flood ($BBfl_i$), wind (BBw_i), earthquake ($BBeq_i$), and collision ($BBcol_i$) is predicted using Eqs. 3.16, 3.17, 3.18, and 3.19:

$$BBfl_i = \alpha_{fl_i} \frac{\alpha_{fl_i} BVRFl_i}{\sum_{j=1}^{m} \alpha_{fl_j} BVRFl_j} \times Rfc \tag{3.16}$$

$$BBw_i = \alpha_{w_i} \frac{\alpha_{w_i} BVRWd_i}{\sum_{j=1}^{m} \alpha_{w_j} BVRWd_j} \times Rfc \tag{3.17}$$

$$BBeq_i = \alpha_{e_i} \frac{\alpha_{e_i} BVREq_i}{\sum_{j=1}^{m} \alpha_{e_j} BVREq_j} \times Rfc \tag{3.18}$$

$$BBcol_i = \alpha_{col_i} \frac{\alpha_{col_i} BVRCo_i}{\sum_{j=1}^{m} \alpha_{col_j} BVRCo_j} \times Rfc \tag{3.19}$$

Where:

BVRFl, BVRWd, BVREq, BVRCo, α_{fl} , α_w , α_e , and α_{col} are explained in Figure 3-11.

m : Total number of bridges in the network that action should be taken on

3.5.3.2 Vulnerability of a Railway Bridge and its Components to Environment and Fatigue

The vulnerability of the component of the bridge will be shown by CVREn. As explained previously, CVREn is calculated based on the weighting factor related to live load and the future condition of the component. The future condition of the component can be predicted based on probabilistic processes such as the Markov method (Agrawal et al., 2010). The future condition of each component (CMav) will be calculated by multiplying the transition probability matrix by the current condition of the component (e.g. 1 to 5) shown in Table 3-21. The future condition of the component is a number from 1 to 5 and is used in Table 3-21 to obtain C_{fi} .

As mentioned previously, the calculation of the future condition of the components (CMav) was outside of the scope of this research and was conducted by other researchers involved in the main project (LCBMR). However, CVREn which shows the vulnerability of the component is calculated based on SRP. The deadlines for taking action related to inspection and repair and maintenance of the components is identified using Table 3-22.

Table 3-21 Calculation of C_{fi} based on the future condition of the components

Future condition of the components (CMav)	**Description of the condition**	$C_{fi} = 1/(1-(LC_f/100))\times 100$
1	$LC_f < 5\%$	$C_{fi} = 105$
2	$5\% \le LC_f < 15\%$	$C_{fi} = 118$
3	$15\% \le LC_f < 25\%$	$C_{fi} = 134$
4	$25\% \le LC_f < 35\%$	$C_{fi} = 154$
5	$35\% \le LC_f$	$C_{fi} = 182$

Table 3-22 Vulnerability of the components to environmental and fatigue and deadlines for taking action

Level of vulnerability	**Description of vulnerability**	**Action to be taken** *(after the prediction time)*	
		Inspection	**Repair or Replacement**
Level FC1	CVREn < 75	Regular (every 2 years)	Not required
Level FC2	75≤ CVREn < 80	Within 1 year	Regular maintenance
Level FC3	80 ≤ CVREn < 85	Within 6 months	Repair in 1year
Level FC4	85 ≤ CVREn < 90	Within 3 months	Repair in 6 months
Level FC5	90 ≤ CVREn	Within 1 month	Repair in 3 months

The budget assigned to each bridge (e.g. bridge *i*) associated with environmental effects and fatigue ($BBev_i$) is predicted using Eq.3.20:

$$BBev_i = \beta_{ev_i} \frac{\beta_{ev_i} BVREn_i}{\sum_{j=1}^{m} \beta_{ev_j} BVREn_j} \times Rfc \qquad 3.20$$

Where:

$BVREn$ and β_{ev}: Explained in Figure 3-11

m : Total number of bridges in the network that action should be taken on

3.5.4 Future Condition of Railway Bridges and their Ratings in a Network

After calculating the vulnerability of the components and the bridge to each critical factor, the future condition of the structure (BFCR) is predicted using Eq. 3.2. In this equation, the contribution of each critical factor towards bridge deterioration is taken into account. BFCR shows the prediction of the future condition of the railway bridge, and its rating based on its future condition among other railway bridges. Taking into account the current condition of the bridge BCCR and future condition of the bridge BFCR, provides engineers with an indication of how quickly the condition of a bridge will deteriorate.

3.5.5 Current and Future Condition of Railway Bridges and their Ratings in a Network

At this level a number (BOCR) is calculated by using Eq. 3.3. This value shows the current and future condition of the railway bridge and its current and future condition rating among others. In Eq. 3.3, parameters γ_1 and γ_2, mentioned earlier and briefly explained, are used. These parameters combine the current and future condition of the bridge and provide an indication of the extent of vulnerability of the bridge within a specific period. Eqs. 3.21 and 3.22 are used to calculated γ_2 and γ_1. Larger γ_2 shows the speed of bridge deterioration.

$$\gamma_2 = \frac{BFCR - BCCR}{BCCR} \qquad 3.21$$

$$\gamma_1 = 1 - \gamma_2 \qquad 3.22$$

By using SRP, contrary to current practical rating methods, engineers can identify the effect of damage in any component of the bridge on the whole structure by performing structural analysis. In addition, they can reliably determine the most critical and vulnerable components and most damaged structures at the network level and deadlines for taking action. This information on the current and future conditions of the components and bridges and deadlines for taking action are extremely important for identifying the best time for intervention. The best time for intervention before the identified deadlines based on SRP are calculated after taking into account other non-structural factors such as cost, human and social factors and through prioritization and optimization processes in BMS.

3.6 CONCLUDING REMARKS

This chapter introduced the Synthetic Rating Method and its procedures for rating railway bridges. The method determines the current and future condition of each bridge and its components in a network of railway bridges and their components, and identifies their ratings among them. The synthetic rating equations are the main component of SRP. These equations include parameters that take into account the risk associated with critical factors, and parameters that evaluate the effect of each critical factor on the structure. The critical factors include live load, flood, collision, earthquake, wind, and environment. In order to quantify the risk parameters related to critical factors, a new method was introduced in this chapter. This method adopts the Analytic Hierarchy Process (AHP) and available risk assessment procedures in design standards.

The second type of parameters of the synthetic rating equations are the weighting factors associated with the criticality and vulnerability of the component. To calculate the weighting factors, a new method was introduced in this chapter. For the first time this method uses the demand by capacity (D/C) ratios of the components as weighting factors. D/C ratios are calculated by conducting structural analysis and design, or measured using SHM systems. These methods of determining the D/C ratios of components are deterministic, and the most reliable method for identifying the safety and serviceability of the bridge and its components in the network. D/C ratios of components associated with each critical factor are calculated or measured and the relevant criticality and vulnerability of the components to each critical factor can therefore be identified. By utilizing the SHM systems, the criticality and vulnerability of the components can be directly and continually determined, and the results will be highly reliable. According to the method, all components of a railway bridge were placed into 3 categories, including structural components, non-structural components and structural details. For each category, the method for identification of the criticalities and vulnerabilities of the components were explained. Criteria were introduced to determine the deadlines for taking action including inspection, repair and maintenance, and structural analysis. Based on these criteria, engineers and managers can make decisions on the condition of the components and the bridge at different stages. In defining the stages, the availability of the resources were taken into account. Hence, resources can be efficiently utilized.

Chapter 4: Dynamic effect of train load on weighting factors of components

As the live (train) load and the associated weighting factors are important, this chapter specifically focuses on the calculation of those weighting factors. Among all weighting factors, the weighting factors associated with the live load directly show the safety and serviceability of the railway bridge at its current condition. Weighting factors other than live loads are related to the future condition of the bridge and considered for preservative actions. The live load is applied to the structure very frequently, but others may or may not happen during the lifetime of the bridge. Another reason for conducting more detailed research on the live load in this chapter, is the importance of the dynamic effect of this load on the structure, as discussed in this chapter. Moreover, other weighting factors are calculated using standard design loads, but live load weighting factors should be calculated based on the real loads, which are applied to the structure.

According to the review of the literature, in order to identify the criticality of the structural components to train load, their susceptibility to variations in the magnitude of the train load and/or speed of the train have to be taken into account. Although in the past there has been numerous literature on the study of structural behaviour of bridges under moving train loads, the capacity of the different components such as columns and beams have not been taken into account. The focus of the previous studies was mainly on identifying the dynamic forces applied on components and the associated stresses and strains in the components of the bridge, and not on determining their safety and serviceability for carrying loads by considering the capacity of the components. As mentioned in the previous chapter, this research is the first to focus on evaluating the sensitivity of the critical components of a bridge to the train loads by calculating the demand/capacity ratios (e.g. weighting factors associated with the criticalities of the components of the bridge). The results can be used for quantifying the criticality of the components. Demand means the internal stresses generated in components due to live and dead loads. The capacities of the different components are the combined strength capacities for carrying internal axial forces and moments and are calculated based on properties of the structural member, e.g. beams, columns and diaphragms. For instance, simply supported beams are prone to bending moments, and therefore their capacity will be their strength towards bending moments, but the capacity for columns that are subjected to axial and bending forces will be calculated based on the combined effects of these forces.

The results of this study illustrate how D/C ratios are used to calculate the criticality weighting factors of the components of the railway bridges. In addition, they show the effect of applying load and speed restrictions on vulnerable railway bridges. The publication based on this chapter can be seen in the reference list (Aflatooni et al., 2015).

4.1 FINITE ELEMENT MODELLING

To investigate the impact of the increase of load and the speed of the train on the critical structural components of the railway bridge, a 3D finite element model of the bridge was created in this research using CSI Bridge Software[1]. The effect of the track structure including the ballast, track, etc. on the dynamic responses of the bridge was identified to be insignificant according to the study reported by Cheng et al. (2001). Since the present study considered a full scale bridge (similar to real bridges), details such as rail, sleepers, and ballast were not taken into account in the scope of this section of this research.

Figure 4-1 shows the geometry of the bridge under consideration. The bridge was designed and checked for different load combinations based on AASHTO LRFD (2007), ACI 318-05/IBC (2005), and AISC360-05/IBC (2005). All of the requirements of the above codes including stress ratio limits, deflection limits, stress reduction factors, and other specifications were taken into account. The US standards were used here to show that different countries could use their own design standards to calculate the demand by capacity ratios of the components, and investigate the safety and serviceability of their bridges based on their own rules and regulations. Any country can use its own design standards for this purpose.

Two bents and two abutments supported the whole deck, and three columns transferred the loads of each bent (Figure 4-1 and Figure 4-4). Circular columns e.g. C1 and C2 as shown in Figure 4-1c and Figure 4-4, with 7000 mm clear height and 700 mm

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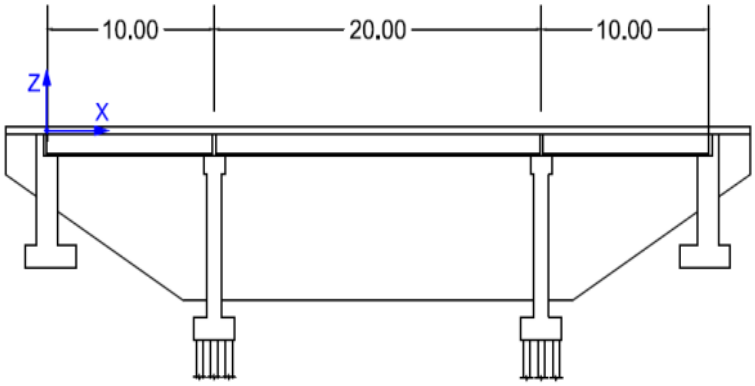
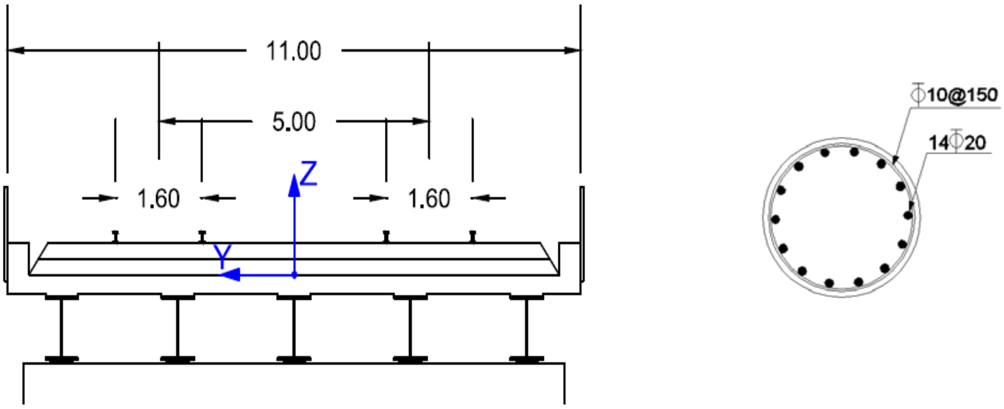
[1] CSI Bridge is a structural and earthquake engineering software, developed by Computers and Structures, INC. 1995 University Avenue Berkeley, California 94704 USA.

diameter were considered. Clear height means the length of the column from the top of foundation to the bottom of the bent beam. Fourteen Nos. of 20Ø steel bars were used in the columns, as longitudinal reinforcement while 10Φ bars at 150mm spacing were provided for confinement. L100×100×10 were utilized for diaphragms D1 to D3, as shown in Figure 4-4. The spacing between diaphragms was 5 meters.

The composite deck had I steel girders (e.g. P1 to P6 as shown in Figure 4-1a and Figure 4-4). The height of the I section was 1170 mm, thickness of flange was 30 mm, thickness of web was 16 mm. The thickness of the concrete slab was 300mm and it was modelled with shell elements. The interaction between the concrete slab and I section of the deck was taken into consideration. The two side spans were 10 m long and the middle span was 20 m. Table 4-1 shows the section properties of the bridge components.



b) Spans



a) Deck

c) Column Section

Figure 4-1 Geometry of the structure and the cross section of the columns

Table 4-1 Frame section properties

Section Name	Material	Shape	Area m^2	I33 m^4	I22 m^4	AS2 m^2	AS3 m^2
Abutment	Concrete	Rectangular	4.730000	8.818651	0.394167	3.941667	3.941667
Cap Beam	Concrete	Rectangular	1.300000	0.108333	0.183083	1.083333	1.083333
Column	Concrete	Circle	0.384845	0.011786	0.011786	0.346361	0.346361
L100	Steel	Angle	0.001900	1.800E-06	1.800E-06	0.001000	0.001000
PG1	Steel	I/Wide Flange	0.038760	0.008648	0.000215	0.018720	0.017500

The spans were simply supported structures. The reason for conducting this research on a simply supported railway bridge was that these types of bridges are widely used in Australia and therefore, their maintenance cost is high. Another reason for modelling a three span bridge was to take into account different load conditions, as train load can be on one, two or all three spans at a time.

Although the spans were simply supported because of the continuity of the train load, the deflection of columns could change the supporting condition of the middle span and the vibration of whole bridge. At bent supports, translations in all directions were fixed and all the three rotations about their local axis were free. At the abutments, translation in vertical direction and rotation about longitudinal axis were fixed and all other degrees of freedom were free.

Figure 4-2 shows the train load applied to the bridge. Two trains moved across the bridge in opposite directions with the same speed, and entered the bridge at the same time. Linear dynamic structural analysis was conducted for different speeds and loads. In order to capture dynamic effects, time history (direct integration) load case was selected instead of static moving load case. The Hilber-Hughes-Taylor (HHT) dynamic time integration method, which is an implicit method for solving transient problem, was used. HHT is unconditionally stable for linear problems (Hilber et al., 1977). In direct integration method, unlike mode superposition method, the dynamic equations of motion (e.g. Eq. 4.1) are integrated through numerical method and prior to any transformation of the equations to any other forms (Bathe, 1982).

$$M\ddot{U} + C\dot{U} + KU = R \tag{4.1}$$

Where, *M*, *C* and *K* are respectively mass, damping and stiffness matrices. Vector *R* is external load and time dependent, $\ddot{U}$, $\dot{U}$, and U are respectively, acceleration, velocity and displacement vectors.

Transient time history motion type with the time step size of 0.05 seconds was considered. Time integration parameters are shown in Table 4-2. They were used in the solution of the equation of motion (e.g. Eq. 4.1).

Table 4-2 Integration parameters

Gamma	**Beta**	**Alpha**
0.50	0.25	0.0

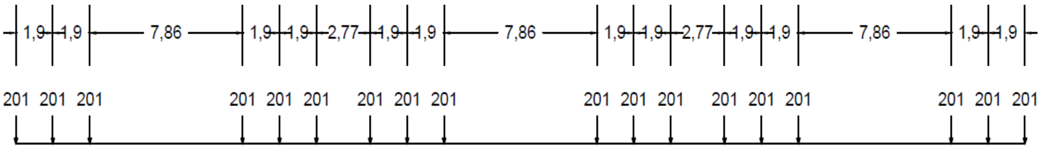


Figure 4-2 Moving load (forces are in kN and distances are in meter)

The dead loads applied to this bridge were the weight of the structural components calculated by CSI Bridge Software. The magnitude of the superimposed dead load on the deck, due to weight of ballast, rail, sleepers, and non-structural components, etc., were calculated to be 10 kN/m^2 and applied to the bridge.

4.2 VALIDATION

In order to show that the dynamic behaviour of the model is similar to real bridges, the natural frequencies of twenty real bridges with respect to their span lengths investigated by Chan and O'Connor (1990) and shown in Table 4-3 were used. The bridges are located in Australia. Similar to the model developed in this research, these bridges are simply supported bridges.

As observed, the lengths of the span of the bridges mentioned in Table 4-3 were between 9.094 m to 28.75 m and the span length of the middle span of the model developed in this research was 20 m. Therefore, in order to validate whether the dynamic behaviour of this model was similar to real bridges, it was necessary to derive an equation that estimated the relationship between the span length of a real simply supported bridge with its dominant natural vertical frequency.

Table 4-3 Summary of natural frequencies for composite concrete slab and steel girder bridges (Chan and O'Connor, 1990)

Bridge	**Span L(m)**	***f* (Hz)**	**Bridge**	**Span L(m)**	***f* (Hz)**
Six Mile Creek (1st)	11.28	10.8	Beatrice Creek	9.094	8.0
Six Mile Creek (2nd)	13.72	8.0	George Creek	14.95	4.5
Bremer River (1st)	11.43	10.3	Coomera Overpass	20.95	2.2
Bremer River (2st)	13.72	8.1	Basin Creek	20.75	5.7
Goodbye Creek	13.38	7.9	Pioneer River	25.0	4.0
Sandy Creek	11.276	12.2	Currumbin	27.95	4.4
St. Aranadus Creek	11.4	10.3	Black River	23.95	4.7
Deebing Creek	15.0	3.9	Coochin Creek	28.75	4.2
Armstrong Creek	13.95	4.9	Rollingstone Creek	22.95	5.2
Emerald Creek	16.95	3.9	Plane Creek	25.8	3.9

In above table:

L : span length

f : natural frequency of bridge

Figure 4-3 shows the relationship of the span length with the natural frequency of the bridges mentioned in Table 4-3. According to this figure, by increasing the length of the bridge span from almost 9m to 23m, the natural frequency will decrease.

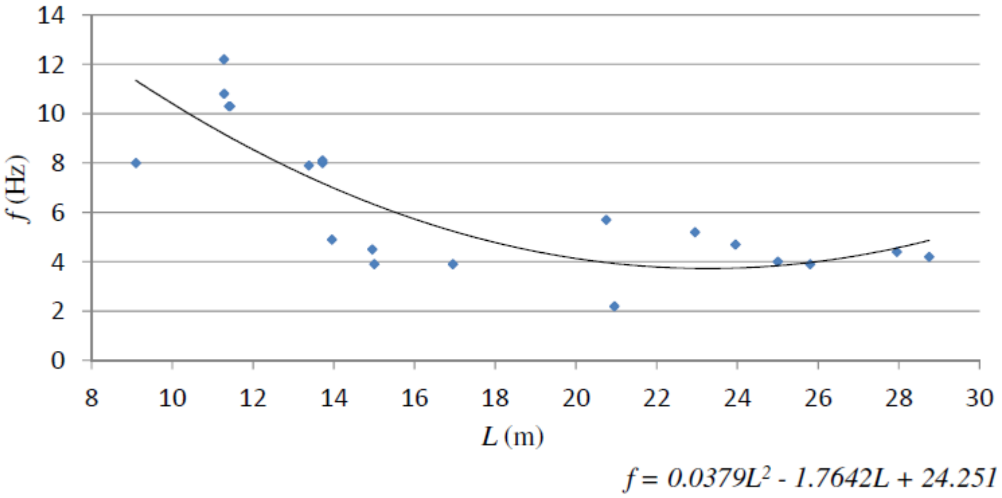


Figure 4-3 The relationship between span length and natural frequency of the above bridges

Based on Figure 4-3, Eq. 4.2 can be formulated, which may represent the relationship between span and natural frequency of real bridges of the type considered here. A second order function was selected for Eq. 4.2, considering that in simply supported beams, the frequency is related to the second order of the span length.

$$f = 0.0379L^2 - 1.7642L + 24.251 \tag{4.2}$$

From Eq. 4.2, for the span L = 20(m), the frequency can be calculated as 4.127 Hz, which is close to the natural frequency of the developed model in this research (e.g. 3.97 Hz as shown in Figure 4-7). The 20m span is equal to the span length of the middle span of this model. Although it is obvious that the natural frequency changes based on the stiffness and mass of the bridge components; this comparison has been conducted here to verify that the dynamic behaviour of this model can represent the dynamic behaviour of a group of real bridges shown in Table 4-3.

4.3 RESULTS

Structural analyses were conducted on this model considering moving loads with different speeds and magnitudes. Speeds from 20 to 300 km/hr, and different magnitudes of live (train) load by multiplying the moving loads shown in Figure 4-2 by coefficients from 0.8 to 1.8. This increase in load was considered to include a variety of train types with different load configurations. For the present study, load combinations of Dead + (coefficients from 0.8 to 1.8) × Live were used for the analysis and design of this bridge. The same load combinations were also used with different speeds. Demand/capacity ratio for different components and different load magnitude and train speed were calculated. Based on ACI 318-05/IBC (2005), columns were checked for axial force and biaxial moments. In addition, they were checked for shear in both directions. Beams and Diaphragm members were checked for stresses due to axial and shear forces and biaxial moments according to AISC360-05/IBC (2005). The calculations were classified in 3 cases as follows.

- Case 1: Increasing the speed of the train from 20 to 300 km/hr, without increasing the magnitude of load. The load factor is considered 1.0 in this case.
- Case 2: Increasing the load by multiplying the train load by the coefficients from 0.8 to 1.8 and without changing the speed. The speed is considered to be 100 km/hr.

- Case 3: Increasing the speed from 60 to 140 km/hr and increasing the magnitude of load by multiplying the train load by the coefficients from 1.0 to 1.8.

4.3.1 Case 1: Increase in Speed

Figure 4-5 and Figure 4-6 show the demand/capacity ratios of the components: C1 and C2, P1 to P6, and D1 to D3. In this section of the study, the focus was on the effect of changing speed on the demand/capacity ratio of the structural components. To more reliably study the resonance in vibration at different speeds, a wide range of speeds were taken into consideration. Speeds higher than 140 km/hr were applied only to show the significant excitation of the bridge. The behaviour of the bridges at high speeds was not studied in this research.

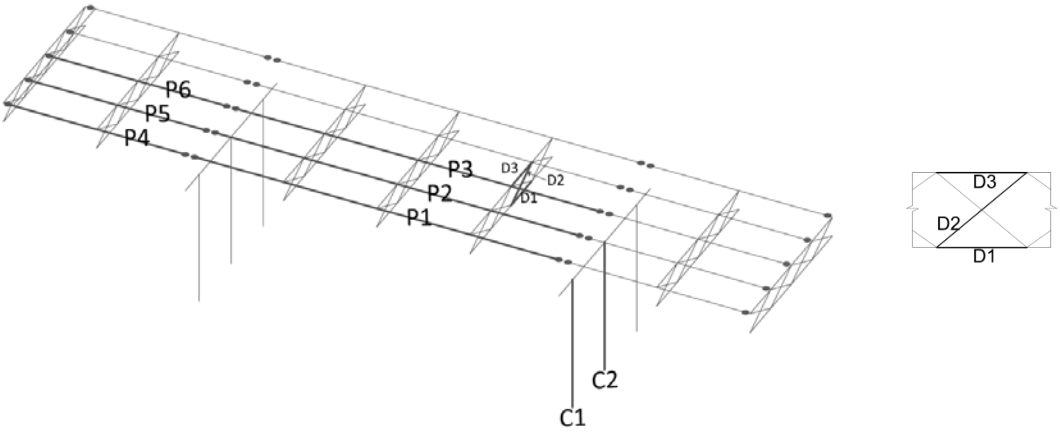
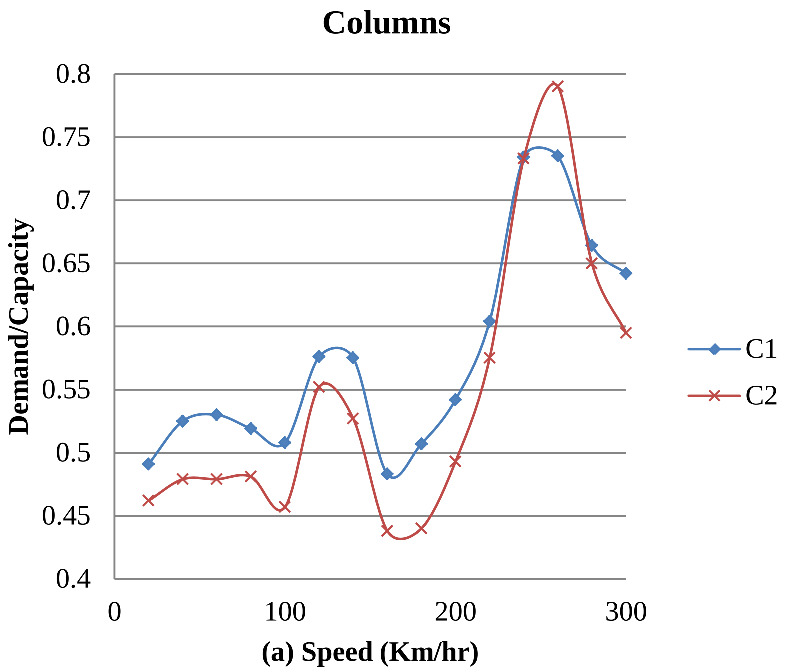


Figure 4-4 Critical component

As can be observed in Figure 4-5, distinctive peaks appeared at certain speeds in the middle span. These occurred at approximately 124 and 258 km/hr in the columns, and approximately 65 and 258 km/hr in girders. These peaks mean larger forces were applied on those components. In order to investigate the reason for this phenomenon, modal analysis was conducted.

To calculate the natural frequencies and mode shapes of the bridge, eigenvalue and eigenvector method was adopted. The dominant vertical natural mode of the structure is shown in Figure 4-7. Figure 4-8 shows the train resultant loads from loads shown in Figure 4-2 applied on the structure with different speeds. The resultant loads considered here were the summation of forces applied by a group of axles of one bogie. By taking into account the resultant forces, the frequency of the load could be more easily calculated. The resultant forces shown in Figure 4-8 were only used to explain that the dynamic behaviour of the model represents the real bridges shown in Table 4-3, and the reason for resonance. For all of the analyses and designs and demand by capacity ratio calculations, including all of the results shown in Figure 4-5 and Figure 4-6 and Figure 4-9 to Figure 4-16, the real load shown in Figure 4-2 was taken into account.



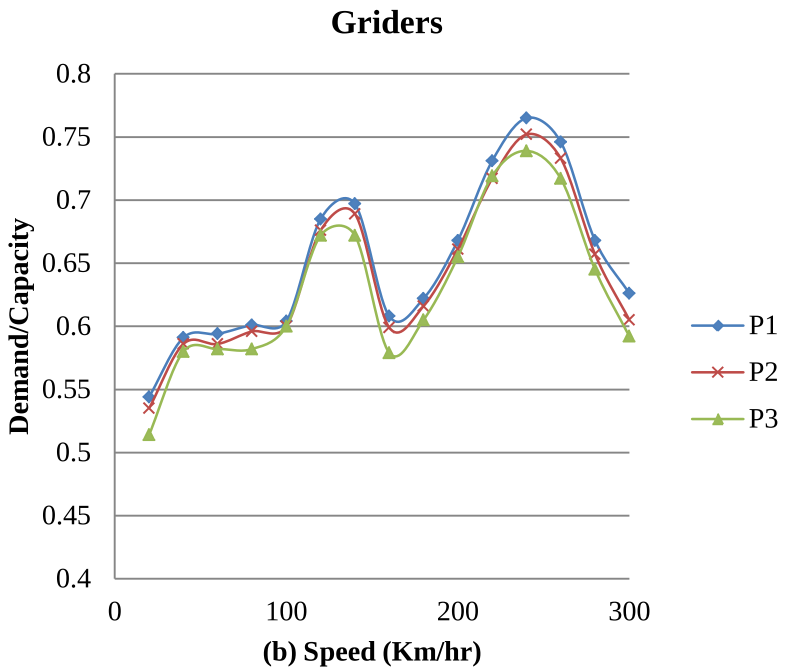
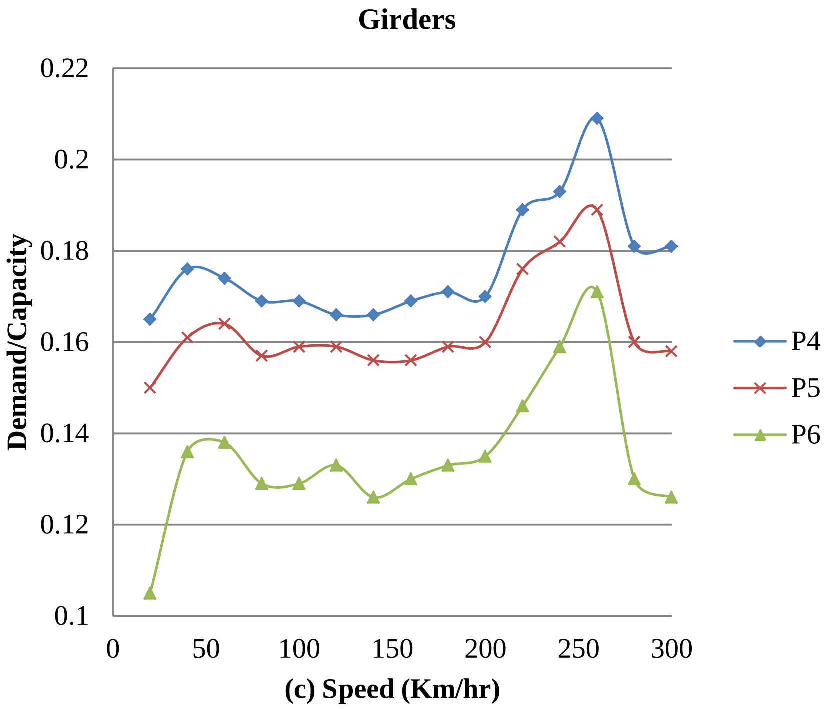


Figure 4-5 Demand/capacity ratio of the bridge columns and girders of the bridge Vs speed of the train



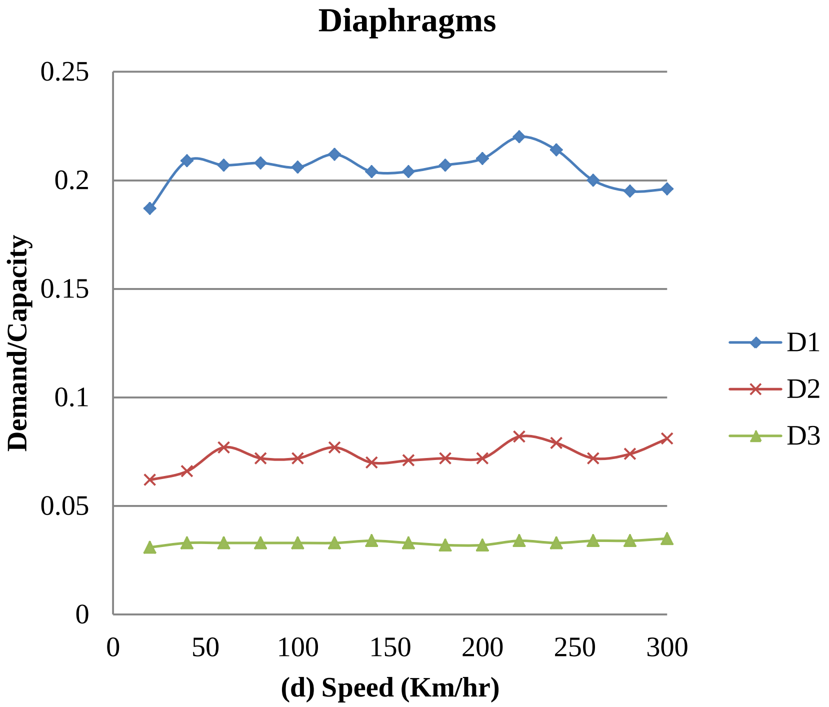


Figure 4-6 Demand/capacity ratio of the bridge girders and diaphragms of the bridge Vs speed of the train

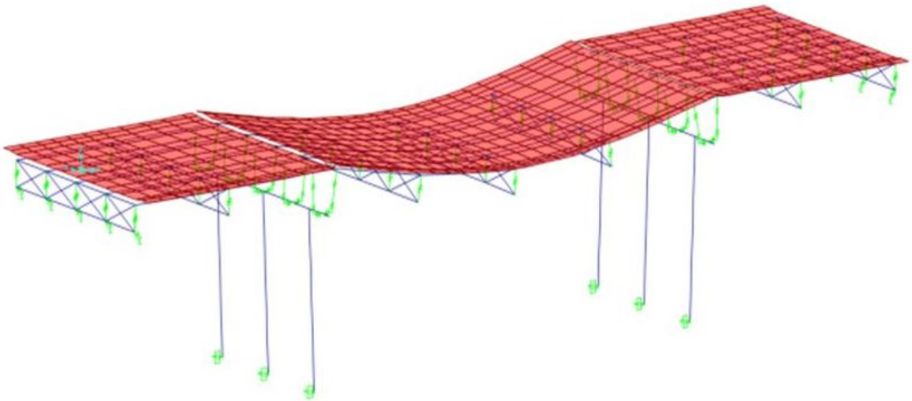


Figure 4-7 The natural dominant mode shape (5^{th}) of the bridge frequency: 3.97 Hz, period: 0.252 Sec

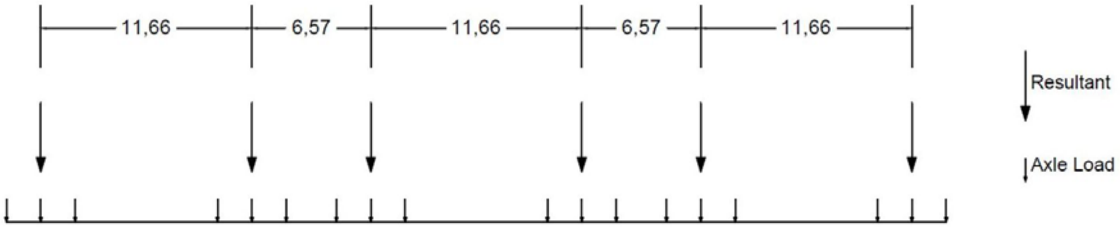


Figure 4-8 The resultant forces of each three close axles

From Figure 4-8, the average distance between the resultant loads is 9.115 m. The frequency of the vehicle load (f_t) can be obtained from Eq. 4.3:

$$f_t = \frac{v}{x} \qquad 4.3$$

Where:
v: Velocity of the train
x: Average distant between the resultant forces

Using the speeds at the peak values in Figure 4-5, the maximum demand by capacity ratios were calculated at the speeds 124 and 258 km/hr. From Eq. 3.3 the frequencies of the loads (f_t) at the above speeds were calculated and are shown in Table 4-4.

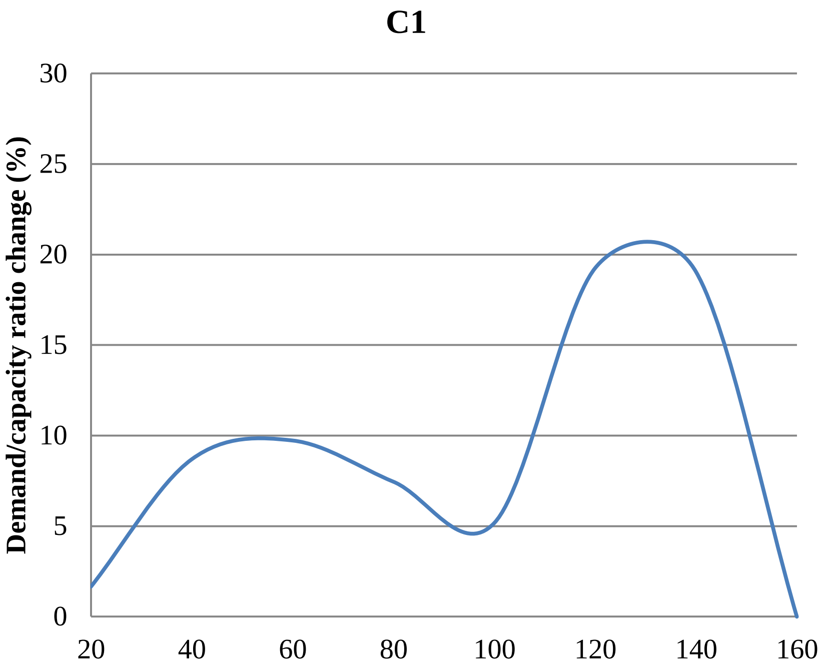
Table 4-4 The speed and frequency of the moving load

$v \ (km/hr)$	$f_t \ (Hz)$
124	3.8
258	7.9

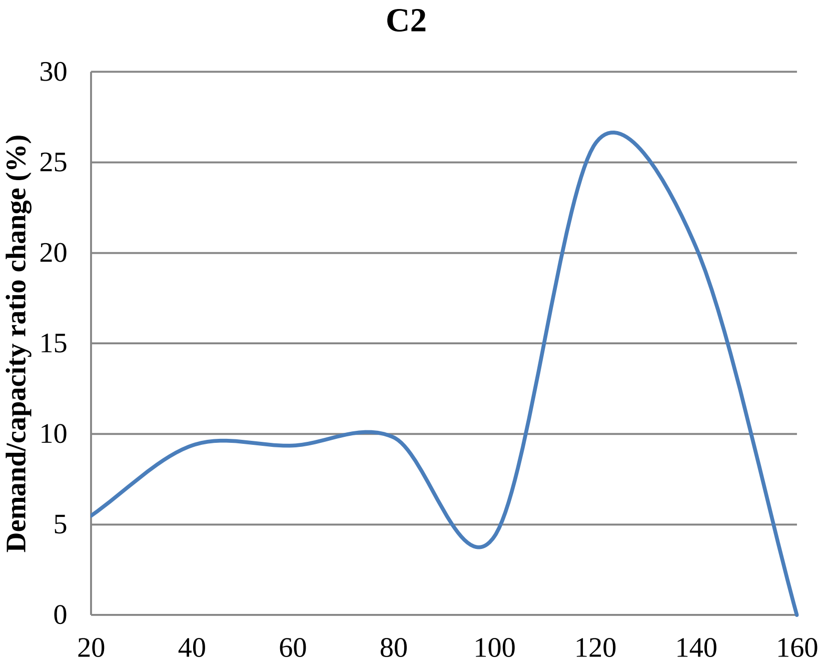
By comparing the frequency of the vehicle with the natural frequency of the vertical mode of the bridge, which is the dominant one, and equal to 3.97 Hz, the reason for occurrence of resonance at peak points can be explained. As can be observed in Figure 4-5 and Figure 4-6, the only peaks occurred when the frequency of the load was equal to the dominant natural vertical frequency of the bridge (as shown in Figure 4-7) multiplied by an integer.

In order to investigate the effect of speed restrictions on simply supported railway bridges based on real conditions, speeds between 20 km/hr to 160 km/hr were taken into account. Figure 4-5 (a) shows that when the train passes over the bridge with the speed of approximately 160 km/hr the minimum demand/capacity would be in C1. It means that applying any speed restrictions would increase this ratio and make the condition worse. Figure 4-9 and Figure 4-10 show the changes in demand by capacity ratios of the components C1, C2, P1 and D1, when the speed of the train reduced from 160 km/hr to 20 km/hr. These figures shows that when the speed limit decreased from 160 km/hr to 120 km/hr, the ratio of demand/capacity would increase about 20% for C1 and 26% for C2. If the current speed limit was 100 km/hr and this speed limit reduced to 60 km/hr, the above ratio would increase about 4% for C1 and 5% for C2.

Figure 4-10 (a) also shows that when the speed reduced from 160 to 140 km/hr the demand/capacity of P1 would increase by about 15%. When the speed reduced from 140 to 100 km/hr, this ratio would also decrease by about 15% and almost equal to the time that this train would pass over the bridge at 160 km/hr. However, from 100 to 40 km/hr this ratio would not change significantly. This means that by applying speed restrictions from 100 to 40 km/hr, the above ratio for girder P1 would not considerably change. The significant decrease in the demand/capacity ratio was seen in almost all components, when the speed reduced beyond 40 km/hr. For high speed trains the increase or decrease of speed could have a significant effect on the demand/capacity ratios. For the model developed here, as can be observed from Table 4-5, if the speed of the train decreased from 260 to 160 km/hr, the demand by capacity ratios would increase by 80%. This increase in load can cause a catastrophic collapse of the structure.

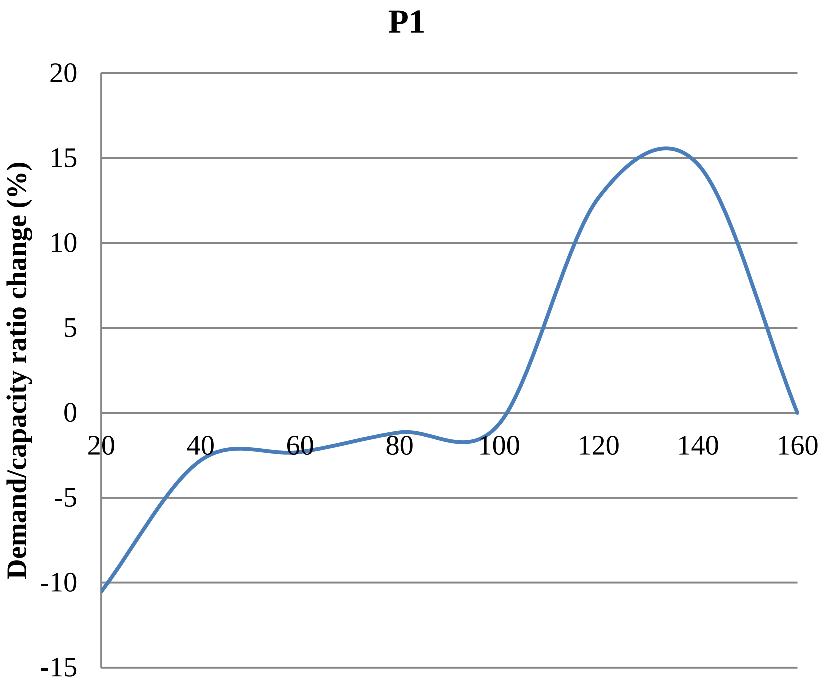


(a) Speed of the train (km/hr)

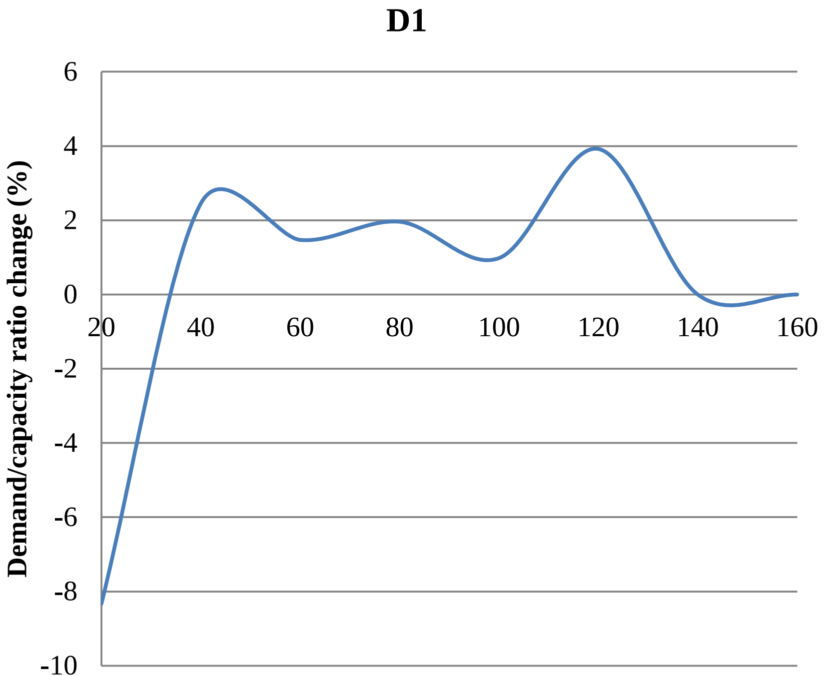


(b) Speed of the train (km/hr)

Figure 4-9 Increase of the demand/capacity ratios of the bridge columns, when the speed of the train reduces from 160 to 20 km/hr.



(c) Speed of the train (km/hr)



(d) Speed of the train (km/hr)

Figure 4-10 Increase of the demand/capacity ratios of the bridge girders and diaphragms, when the speed of the train reduces from 160 to 20 km/hr

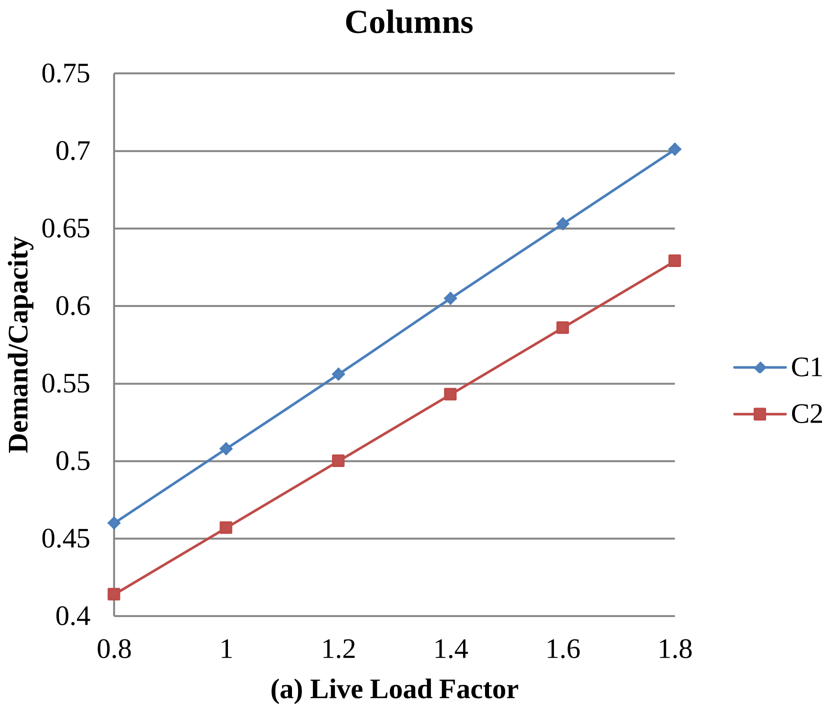
Table 4-5 The maximum increase in demand/capacity ratio in percentage due to the changes in speed of the train from 20 to 300 km/hr

Component	**Demand/Capacity Changes**	**Component**	**Demand/Capacity Changes**
C1	52%	P5	26%
C2	80%	P6	63%
P1	41%	D1	18%
P2	41%	D2	33%
P3	44%	D3	13%
P4	27%		

Table 4-5 shows that columns were more sensitive to the increase of speed than girders, especially the middle column (C2). Changes in demand/capacity ratio in the middle column due to the increase of speed within the range of 20 km/hr to 300 km/hr was about 80% which was almost twice more than each girder in the middle span which was about 41%. The diaphragm components were less sensitive to the increase of speed compared to girders and columns. The results also show that the sensitivity of different components of the same type (e.g. girders) were different and it depended on their position in the structure.

4.3.2 Case 2: Changes in Magnitude of Train Loads

In case two, as mentioned before, the speed (100km/hr) of the trains did not change, but the magnitude of the trains loads were increased from 0.8 times train load to 1.8 times train load. Figure 4-11 and Figure 4-12 show the demand by capacity ratios (weighting factors) of the different components of the bridge. As can be observed in Figure 4-11 and Figure 4-12, by increasing the load, the demand by capacity ratios of all of the different components increased in linear form. However, the rates of increase were different for the different components (columns, girders, and diaphragm).



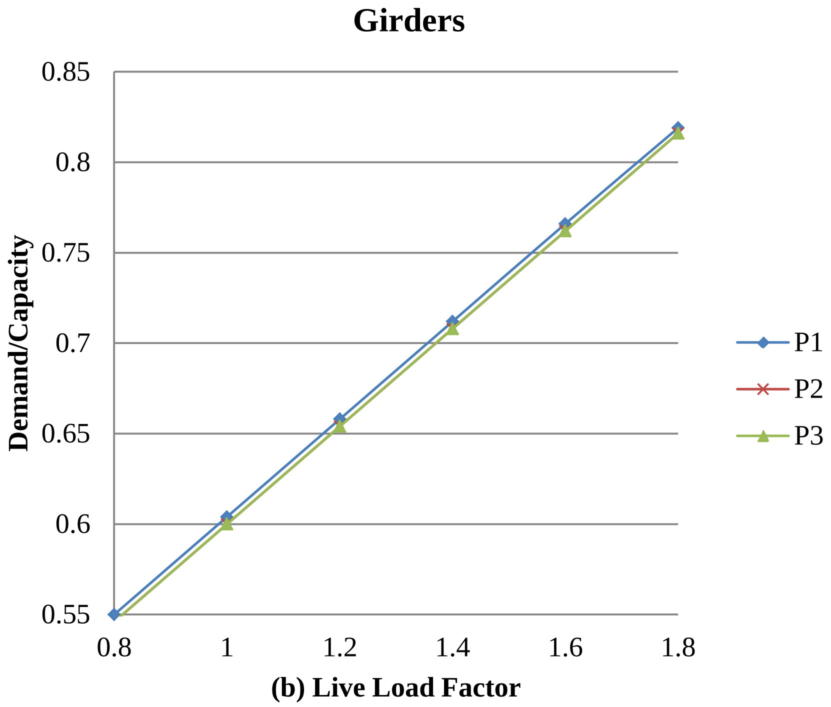
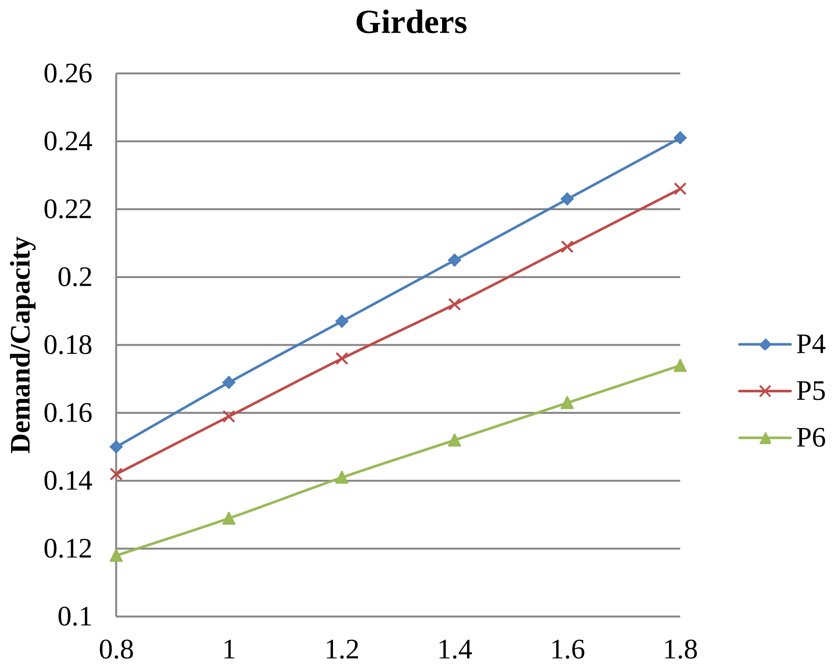
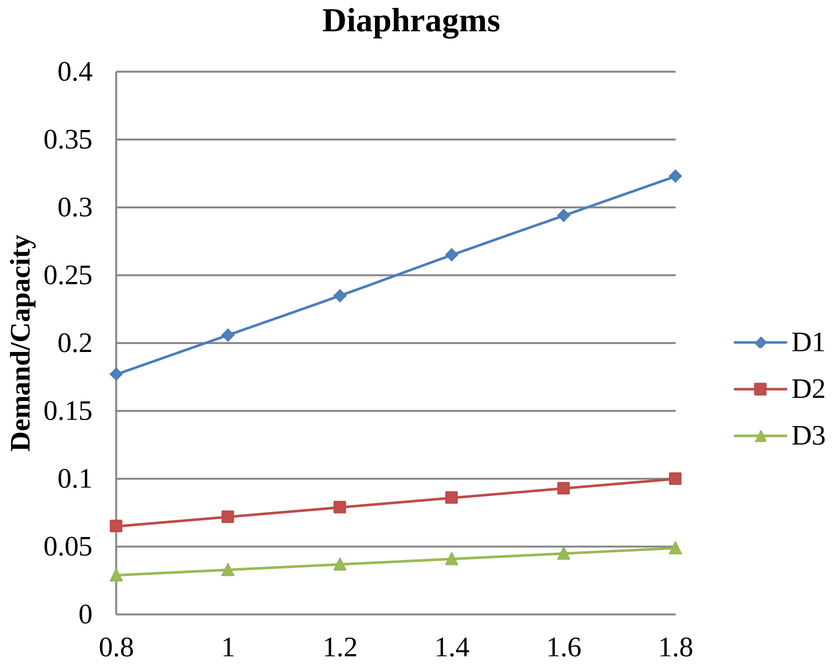


Figure 4-11 Demand/capacity ratio of the bridge columns and girders with respect to the increase of live load when the speed is constant and equal to 100 km/hr



(c) Live Load Factor



(d) Live Load Factor

Figure 4-12 Demand/capacity ratio of the bridge girders and diaphragms with respect to the increase of live load when the speed is constant and equal to 100 km/hr

Table 4-6 shows the maximum increase in demand/capacity ratio in percentage due to the changes of the load from 0.8 times train load to 1.8 times train load. The results also show that except for diaphragm components, the sensitivities of components of the same type to the increase in load, were not considerably different. For instance, by increasing live load from 0.8 times train load to 1.8 times train load, the increase of demand by capacity ratio of all columns were almost identical and equal to 52% and all girders were almost 49%. However, it can be observed that the Demand by Capacity ratio of the diaphragm component D1 increased about 82% when the load increased by 125%, which was about 67% more than girders and 58% more than columns.

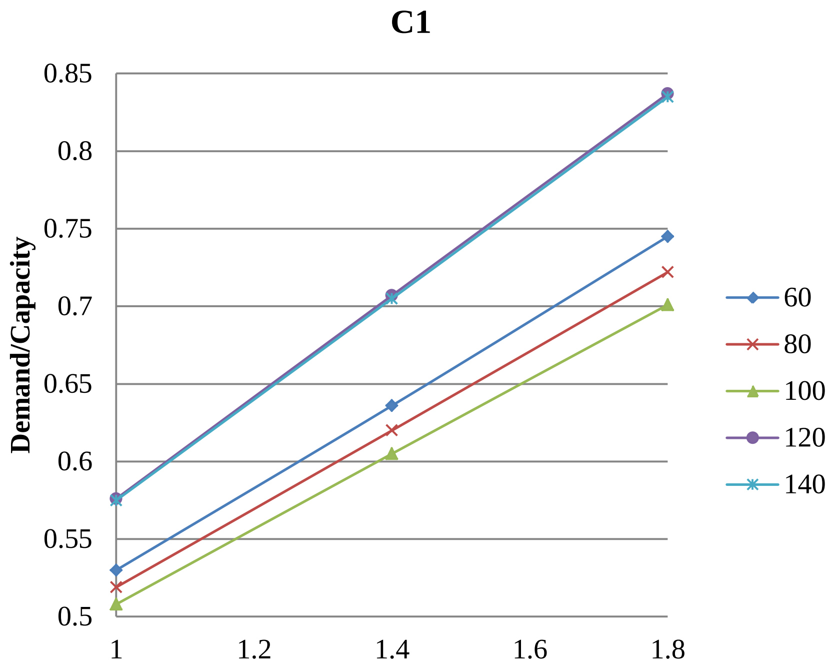
Table 4-6 The maximum increase in demand/capacity ratio in percentage due to the increase of the train live load factor from 0.8 to 1.8

Component	**Demand/Capacity Changes**	**Component**	**Demand/Capacity Changes**
C1	52%	P5	59%
C2	52%	P6	47%
P1	49%	D1	82%
P2	49%	D2	54%
P3	49%	D3	69%
P4	61%		

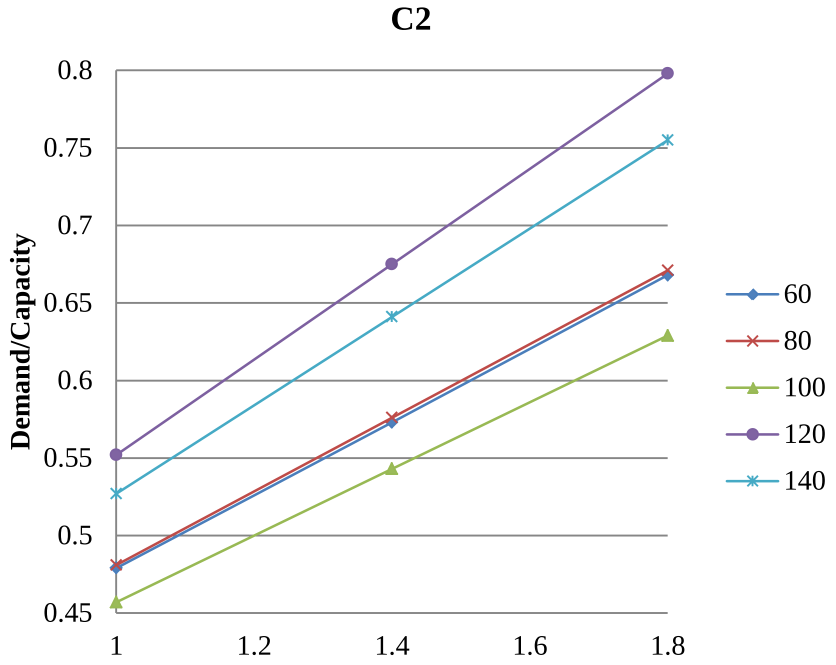
4.3.3 Case 3: Changes in Train Load and Speed

In case 3, the effect of both the increase of load and speed were studied. Figure 4-13 and Figure 4-14 show the effect of both increase of loads and speeds. The load increased from 1.0 × train load to 1.8 × train load and the speed increased from 60 km/hr to 140 km/hr. It can be observed that the dynamic effect of the speed of the train on vertical vibration response of the bridge could have a high impact on the response of the structure including internal forces and displacements in critical components.

For example, according to Figure 4-13, for column C1, the demand by capacity ratio when trains with a 60 km/hr speed passed over the bridge were higher than when trains crossed at 80 or 100 km/hr. Therefore, applying speed restriction on bridges, without detailed investigations, could lead to catastrophic failures rather than fulfilling its intended purpose. In addition, by applying speed restrictions on damaged railway bridges that have lost some of their capacities, the effect of fatigue may become more severe, as a result of a likely increase in the magnitude of internal forces in critical components. Increase in the demand (internal stresses), has an effect on fatigue damage (Polepeddi and Mohammadi, 2000). According to investigations by Imam et al. (2008), the increase in loads significantly affected the remaining fatigue life of railway bridges.

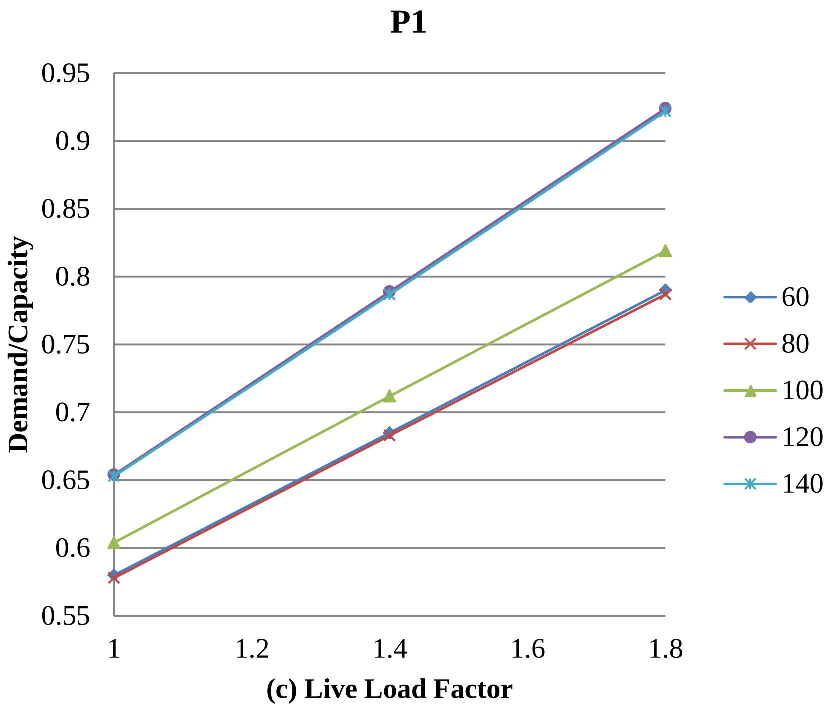


(a) Live Load Factor



(b) Live Load Factor

Figure 4-13 Demand/capacity ratio of the bridge columns with respect to the increase of live load and speed (speed unit is km/hr)



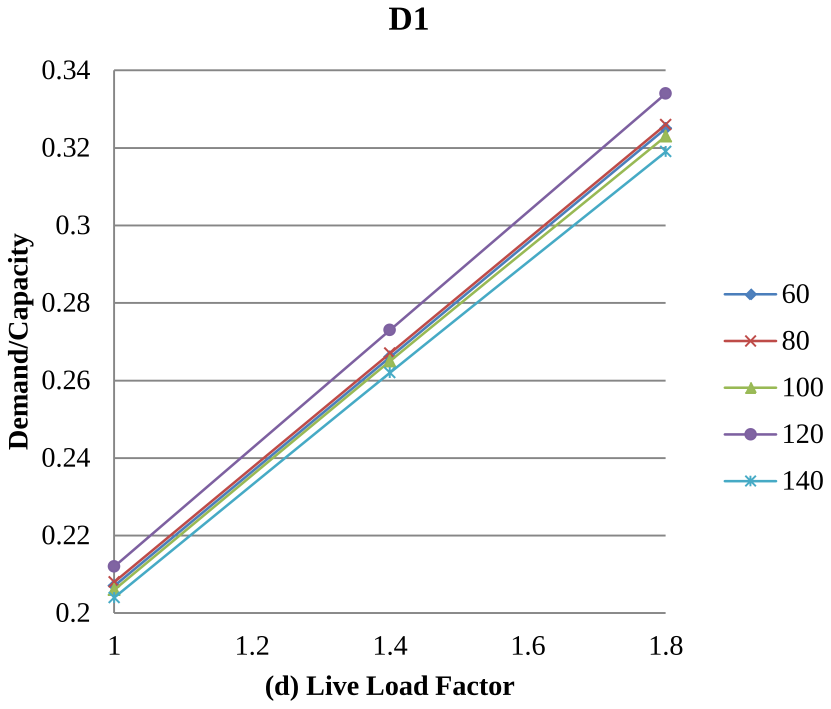
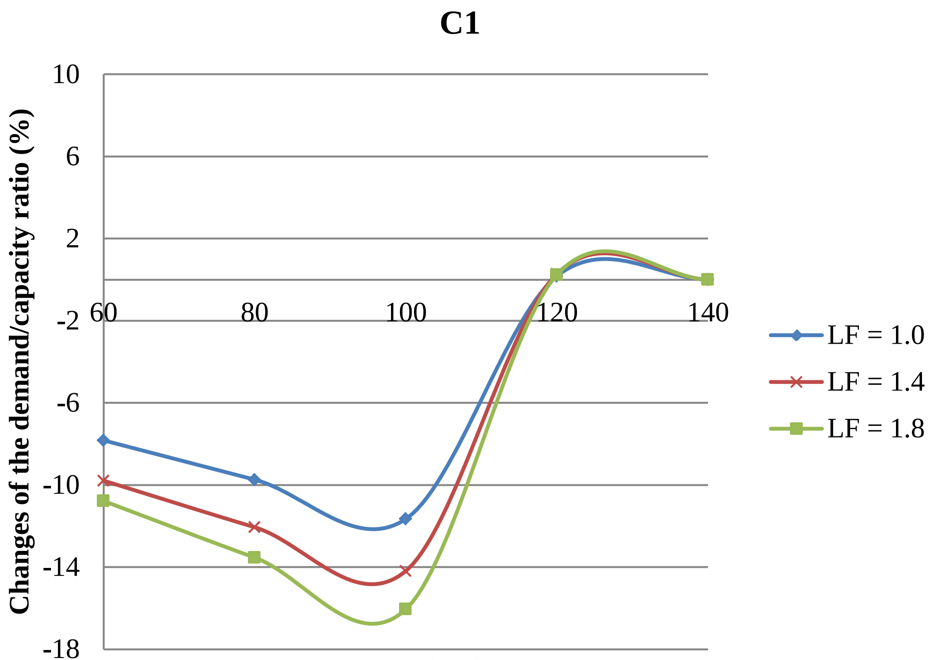
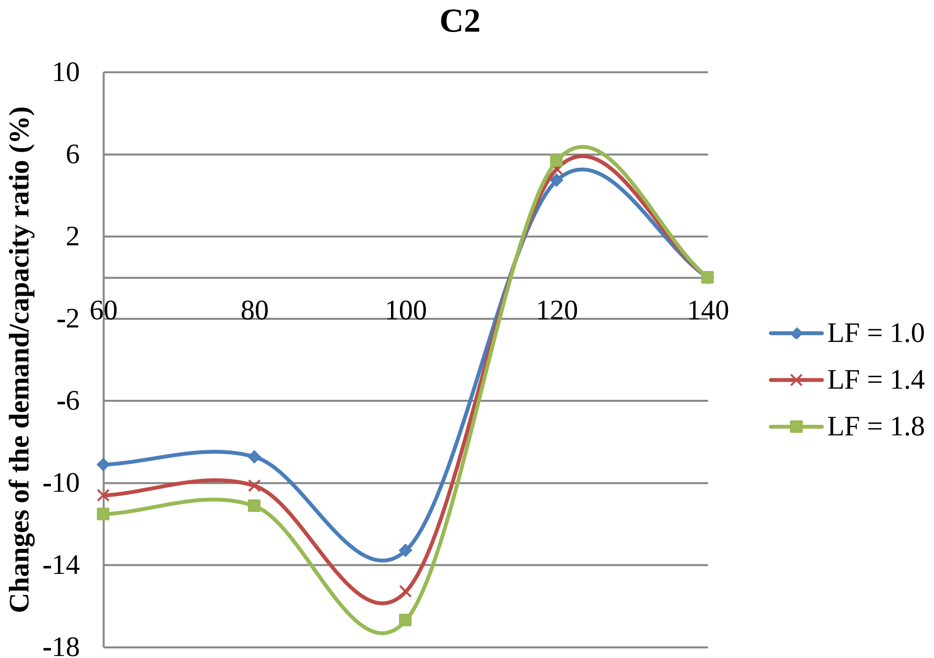


Figure 4-14 Demand/capacity ratio of the bridge girders and diaphragms with respect to the increase of live load and speed (speed unit is km/hr)

As seen in Figure 4-13, by decreasing the speed from 100 to 60 km/hr, the demand/capacity ratios increased by up to 6% in columns for a Load Factor (LF) of 1.8. The changes in demand/capacity ratio of different component were calculated and are shown in Figure 4-15 and Figure 4-16. These figures show that for C1 and C2 and P1, at each specific speed, when the load increased, changes in demand/capacity ratio increased. For D1 these changes were small and did not increase with respect to the increase of the load.

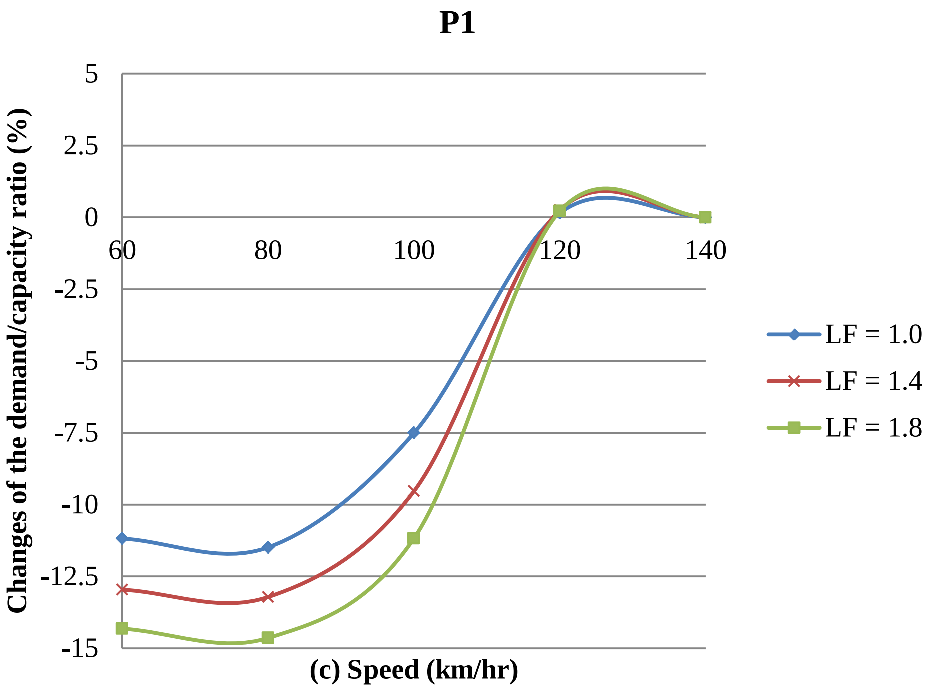


(a) Speed (km/hr)



(b) Speed (km/hr)

Figure 4-15 Changes to the demand/capacity ratio of the bridge columns in percentage with respect to the increase of live load and speed



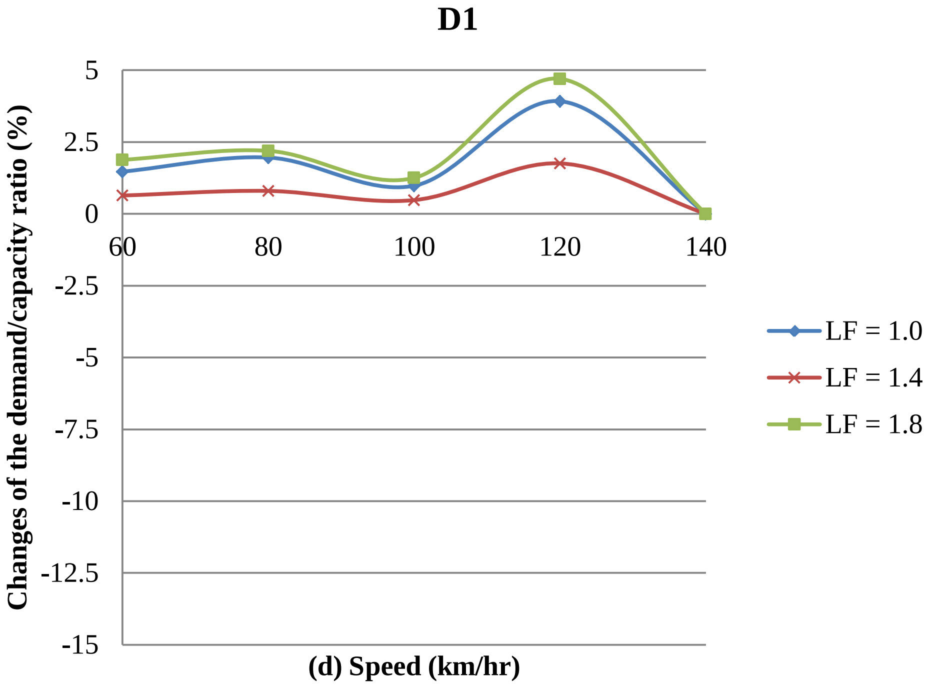


Figure 4-16 Changes to the demand/capacity ratio of the bridge girders and diaphragms in percentage with respect to the increase of live load and speed

4.4 CONCLUDING REMARKS

The results of this chapter show that conducting dynamic analysis on the structure to obtain the weighting factors associated with the criticalities of the components will enhance the reliability of the calculations. The results show the significant effects of increasing speed on demand by capacity ratios (weighting factors) of the critical components. Some components are more sensitive to this increase than others. The outcomes depict that by applying restrictions on speed, internal forces may unexpectedly increase. This means that reducing speed may subject the bridges to more danger than before, especially by increasing the effect of fatigue in the long run. It was identified that the resonance of responses could occur as a result of the equality of the natural vertical frequency of the bridge with the frequency of the live load at certain speeds.

The outcome of this chapter is very significant, as it shows the strategies for applying speed restrictions may need to be revised. According to this study, to avoid resonance of the responses, applying speed restrictions should be based on the frequency of the moving load, which depends on the speed of the train and the configuration of its axles, as well as the natural vertical frequency of the bridge. Therefore, it is suggested to apply different speed limits based on the structural configuration of the railway bridge and train specifications, including train loads and axle spacing, Applying one speed limit to different types of trains would not be an appropriate strategy for decreasing the internal forces in critical components of the bridge. The speed limits should cause the least dynamic effects on the bridge structure. The speed limits should be the minimum values in the figures (e.g. as Figure 4-5 Figure 4-6), which show the relationship between the speeds of the train and the demand by capacity ratios of the components. The speed restrictions for each particular train should not cause resonance in vibration. To evaluate the sensitivity of different components to changes of live load, it is necessary to determine demand by capacity ratios, similar to those in this research, for each specific bridge and for each type of train. The unique, important outcome of this study will be its anticipated influence on the decisions made by engineers and managers for applying load and speed restrictions on vulnerable railway bridges. Moreover, the results can be used for the interpretation of the specific data collected from Structural Heath Monitoring (SHM) systems. Those data are the peak responses of bridge components associated with some specific speeds, which cause resonance in responses. The peak responses are measured through sensors of the SHM systems.

Chapter 5: Application of the Synthetic Rating Method

This chapter illustrates the application of the synthetic rating method at the network level by conducting criticality and vulnerability analyses on two bridges. In presenting this chapter, the practicality of using this method and its advantages over other methods is elaborated. The first bridge is the one introduced in the previous chapter, and the second bridge will be introduced in this section.

According to the Synthetic Rating Procedure (SRP) explained in Section 3.5, the first step is the quantification of the importance of critical factors, which show the contribution of each critical factor towards bridge deterioration. The second step is the calculation of the weighting factors of each component of the bridge associated with different critical factors. The third step is the evaluation of the criticalities and vulnerabilities and ratings of the components and the bridge, using synthetic rating equations, and identifying the deadlines for taking action using SRP. The last part, related to the criticality and vulnerability of the components and bridges at the network level, is shown after conducting similar type of analyses on the second bridge.

5.1 BRIDGE 1

5.1.1 Step 1: Contribution of Critical Factors towards Bridge Deterioration

In this example all critical factors including flood, wind, earthquake, collision and environmental effects were taken into account. The criticality of the live load is estimated when the criticality of the components are calculated in the next section.

Figure 5-1-shows the geometry of bridge 1 and identifies its components. More details about the geometry of the bridge were presented in Figure 4-1 and Section 4.1.

Table 5-1 shows the risks associated with different critical factors. They were determined based on Sections 3.3.3.2.1 to 3.3.3.2.5, and Section 3.3.3.3. Based on the method developed in Section 3.3.3 of this thesis, the importance of critical factors were calculated. *A1* is the pair-wise comparison between factors. Section 3.3.3.3 shows the method and equations for calculating the entries of matrix *A1*. Table 5-2 shows the criticality coefficient of each factor and Table 5-3 shows the contribution of each critical factor towards bridge deterioration. Section 3.3.3.2 and its subsections elaborate the methods for calculating the coefficients shown in Table 5-2. Table 5-3 is the eigenvector associated with the maximum eigenvalue of the matrix *A1*, as discussed in Section 3.3.3.3.

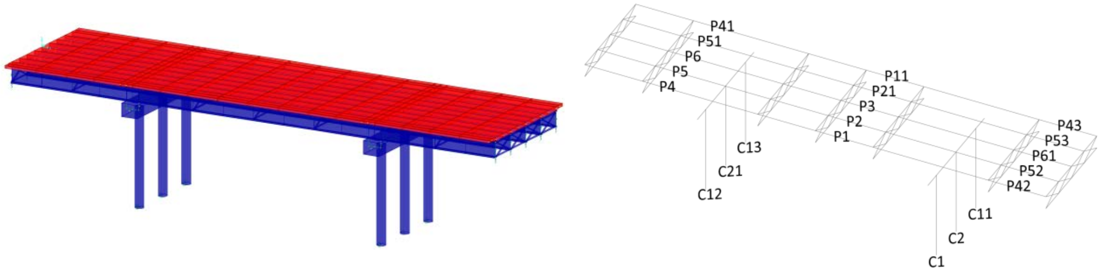


Figure 5-1 Geometry of bridge 1

Table 5-1 The risk associated with the critical factors related to railway bridge 1

Environmental condition:	C
ARI (AS5100.2, 2004)	100
Wind (AS1170.2, 2002)	A4
Z (AS1170.4, 2007)	0.13
K_p (AS1170.4, 2007)	1.8
Traffic volume	B
Cm1 to Cm10	1

Table 5-2 Calculation of the coefficients

C_{ev}	1
C_{col}	1
C_{fl}	1.65051
C_{w}	1
C_{eq}	1.62

$$
A1 = \begin{array}{c|ccccc|}
 & Ev & Col & Fl & W & Eq \\
Ev & 1 & 14.96 & 2.265959 & 748 & 461.7284 \\
Col & 0.066845 & 1 & 0.151468 & 50 & 30.8642 \\
Fl & 0.441314 & 6.60206 & 1 & 330.103 & 203.7673 \\
W & 0.001337 & 0.02 & 0.003029 & 1 & 0.617284 \\
Eq & 0.002166 & 0.0324 & 0.004908 & 1.62 & 1
\end{array}
$$

Table 5-3 Contribution of the critical factors towards bridge deterioration

β_{ev}	0.913163
α_{fl}	0.402992
α_{w}	0.001221
α_{e}	0.001978
α_{col}	0.061040

5.1.2 Step 2: Weighting Factors of each Component of a Bridge Associated with Different Critical Factors

According to the method explained in Section 3.4, the weighting factors of the structural component are the D/C ratios of the component associated with different critical factors. In fact, those weighting factors depict the criticalities and vulnerabilities of the component associated with different critical factors at the time of conducting structural analysis.

Live load: The details of the analysis related to live load were explained in Sections 3.4 and 3.4.1. In Chapter 4, the magnitude and the speed of the load shown in Figure 4-2 was varied to show the dynamic effects of the load on the structure. In this section, the load shown in Figure 4-2 is taken into account as the D/C ratios of the components should be calculated based on the maximum real load that would be applied to the bridge. Two trains with the above load pattern enter the bridge at the same time and from the opposite sides, and travel over the bridge with a speed of 100 km/hr. The weighting factors of the components which are their D/C ratios associated with live load, are calculated by applying 1.2 Dead + Live load to the bridge and conducting structural analysis.

Flood: The weighing factors of the components related to flood were calculated by applying 1.2 Dead + Flood load to the structure and calculating their D/C ratios. The flood forces applied to the bridge include drag and lift forces on piers, drag and lift forces on the superstructure, moment on the superstructure, debris forces on sub and super structures, and log impact forces. The ultimate limit state (ULS) of the above forces can be used for the weighting factors associated with the safety of the bridge, and the serviceability limit state (SLS) can be used for the weighting factors related to the serviceability of the bridge. In this section, only safety weighting factors were taken into account to illustrate the method. AS 5100.2 (2004) was used to calculated the flood forces. At ultimate limit state, it was assumed that the flood level would be about 2 m above the track. Eqs. 5.1 to 5.5 from AS 5100.2 (2004) were used to calculate the flood forces. Figure 5-2 shows the flood forces applied to the bridge, and Figure 5-3 shows the deformed shape of the bridge after applying the above mentioned combination of dead and flood load.

Ultimate drag force on piers (F^*_{du})

$$F^*_{du} = 0.5C_d V_u^2 A_d \tag{5.1}$$

C_d: Drag coefficient

V_u: Mean velocity of water flow for ULS

A_d: Area of pier (height multiplied by the thickness of pier perpendicular to the direction of the water flow)

Ultimate lift force on piers (F^*_{du})

$$F^*_{Lu} = 0.5C_L V_u^2 A_L \tag{5.2}$$

C_L: Lift coefficient

V_u: Same as mentioned in Eq. 5.1

A_L: Area of pier (height of the flow multiplied by the width of pier parallel to the direction of the water flow)

Ultimate drag force on superstructures (F^*_{du})

$$F^*_{du} = 0.5C_d V_u^2 A_s \tag{5.3}$$

C_d: Same as mentioned in Eq. 5.1

V_u: Same as mentioned in Eq. 5.1

A_s: Wetted projected area of the superstructure of a plane perpendicular to the water flow

Ultimate drag force on superstructures (F^*_{Lu})

$$F^*_{Lu} = 0.5C_L V_u^2 A_L \tag{5.4}$$

C_L: Same as mentioned in Eq. 5.2

V_u: Same as mentioned in Eq. 5.1

A_L: Plan deck area

Ultimate drag force on superstructures (M^*_{gu})

$$M^*_{gu} = 0.5C_m V_u^2 A_s d_{sp} \tag{5.5}$$

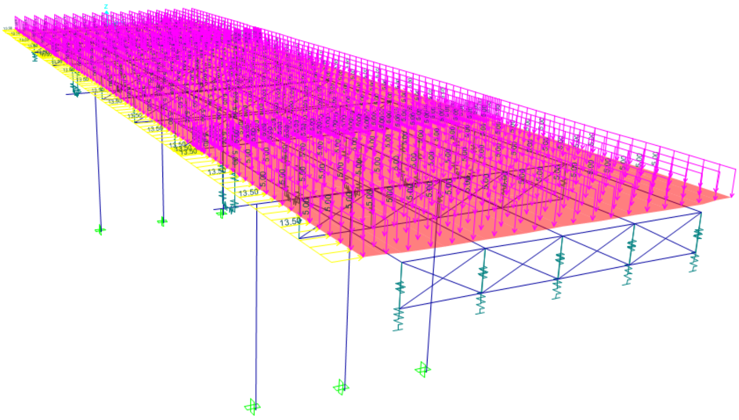
C_L: Moment coefficient

V_u: Same as mentioned in Eq. 5.1

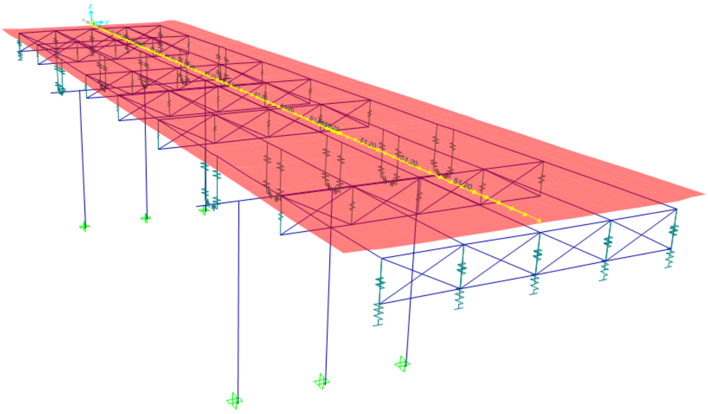
A_s: Same as mentioned in Eq. 5.3

d_{sp}: Wetted depth of the superstructure projected on a plane normal to the water flow

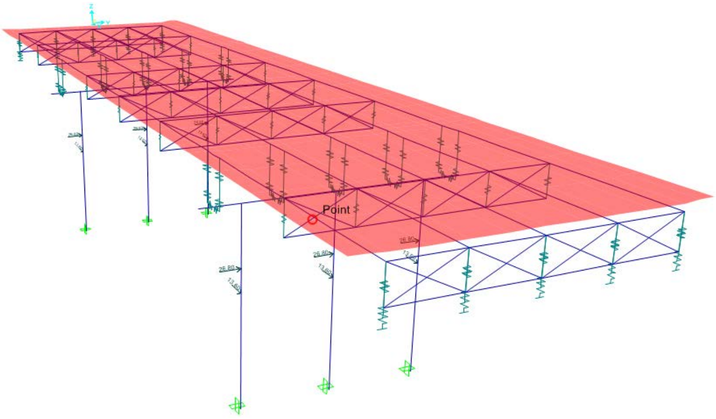
Among all of the preceding forces caused by the flood that can be applied to a bridge, the forces due to debris and log impact were not taken into account for this bridge as these examples are only for illustrating the application of the method. However, they could also be calculated based on the AS 5100.2 (2004).



(a) Forces on superstructure (5 kN/m^2 downward and 13.5 kN/m drag force)



(b) Forces on superstructure (51.2 kNm/m moment)



(c) Forces on substructure (on each pier, 13.6 kN in longitudinal and 26.8 kN in transverse directions)

Figure 5-2 Flood forced applied on the sub and superstructure of the bridge

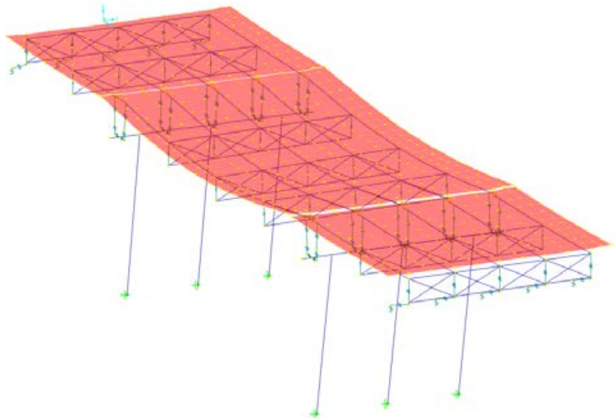


Figure 5-3 Exaggerated deformed shape of the structure subjected to flood forces

Earthquake:

In order to calculate the weighting factors associated with earthquake, the mass of the structure associated with its dead load is taken into account. Table 5-4 shows the parameters considered for response spectrum function and Figure 5-4 shows the response spectrum function applied to the structure based on AS 1170.4 (2007).

In calculating the D/C ratios of columns, the capacity of the column beyond its elastic limit was considered as the demand seismic forces push the structure beyond its elastic limits. The D/C ratios of columns were calculated based on their plastic deformation and not by their internal maximum stresses. As explained before, nonlinear analysis can only be applied to seismic loads, as the structure experiences its elastoplastic or plastic behaviour for only a few seconds. For columns, pushover analysis was performed to calculate the demand/capacity ratios, but for beams 1.2 × Dead load was considered to calculate the demand by capacity ratios of the components based on internal stresses in the components, without taking into account the seismic effects. The reason is that the superstructure moves as a whole (single body). Figure 5-5 shows displacement vs. base reaction for bent 1.

Table 5-4 Response spectrum function definition (AS1170.4, 2007)

Site subsoil class	D
Probability factor (Kp)	1.8
Hazard factor (Z)	0.13
Structural performance factor (Sp)	0.77
Function damping ratio	0.05

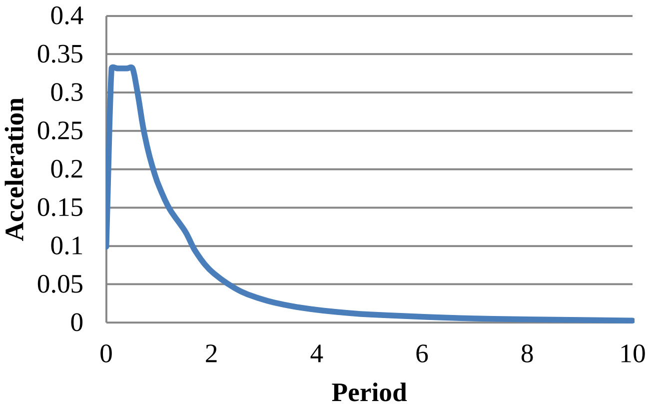
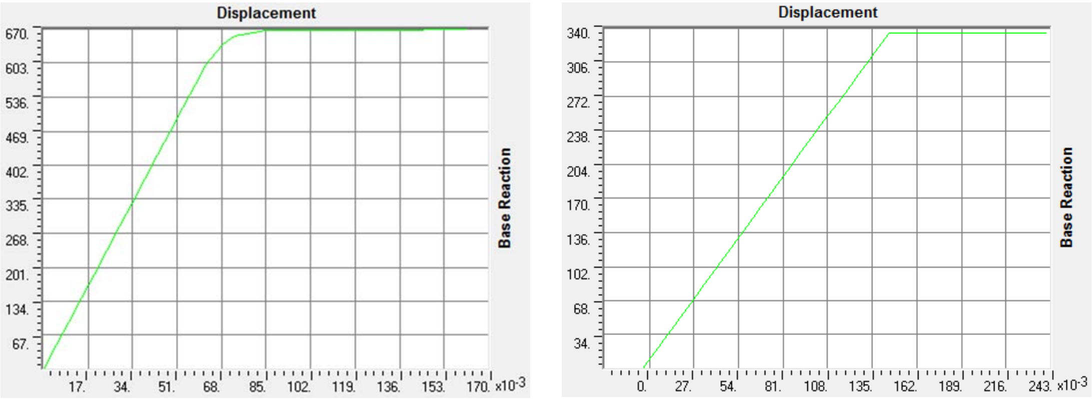


Figure 5-4 Response spectrum function (AS1170.4, 2007)



Transverse direction

(Columns' D/C=0.38)

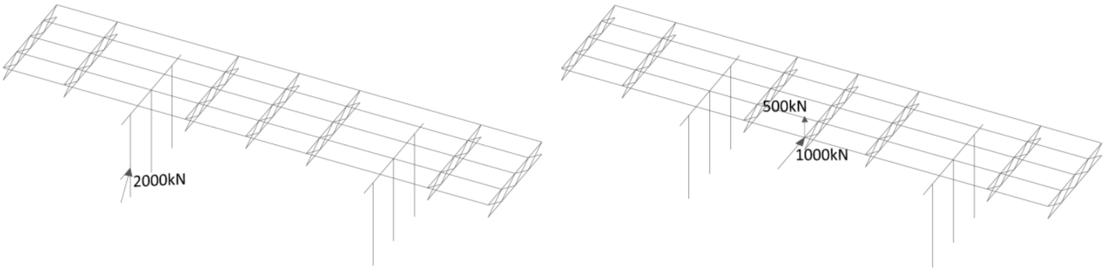
Longitudinal direction

(Columns' D/C=0.25)

Figure 5-5 Displacement (m) vs. base reaction (kN) for bent 1

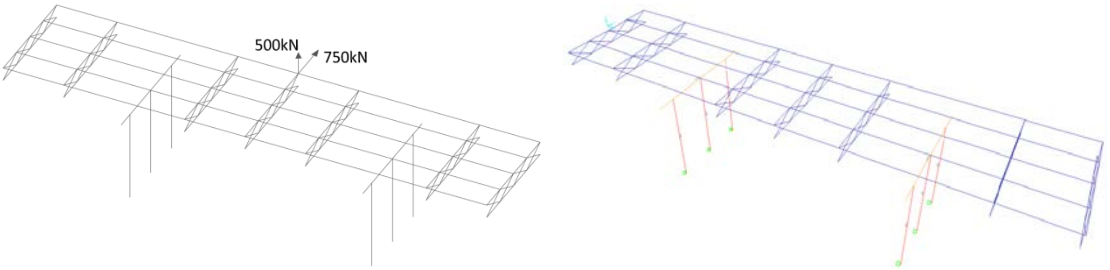
Collision: For this bridge it was assumed that a road passed under the bridge. According to AS 5100.2 2004 a minimum equivalent static load of 2000 kN is considered at an angle of 10° from the direction of the road centre-line. The load should be applied 1.2 meter above the ground level.

The loads applied to the superstructure are 1000 kN towards the bridge, 750 kN away from the bridge and 500 kN vertical load. Figure 5-6 shows the collision loads applied to the structures and the failure in columns. All of the above loads applied to the sub and superstructures are the ultimate limit state loads. The load combination of 1.2 Dead + Collision load is applied to the structure to calculate the D/C ratios of the components. The values shown in column (ix) of Table 5-6 that are related to the condition of the columns of the bridge at the time of performing structural analysis, show that they would fail if they were subjected to collision, as the D/C ratios of the columns would be higher than one. Therefore, protective components should be built for the structure. Table 5-6 shows that if the protective beams cannot carry their loads the diaphragm D/C ratios would reach 80%.



a) Force applied to a column
(it will be applied to each column separately)

b) Forces applied to superstructure
(toward the bridge)



c) Forces applied to superstructure
(away from the bridge)

d) Failure in columns due to collision

Figure 5-6 Collision forces applied to the structure and failure in columns

Wind: The weighting factors of the components of the bridge associated with wind are calculated by applying 1.2 Dead + Wind to the structure and then calculating the D/C ratios of the components. Regional basic design wind speed for a 2000 year average return interval and for region A4 is obtained from AS/NZS 1170.2-2002, which is equal to V_{2000}= 48 m/s. All other parameters are shown in Table 5-5. The wind load is applied to the structure when a train with the height of 3.625 meters is passing over the bridge.

Table 5-5 Wind exposure parameters and wind coefficients

Wind exposure parameters		Wind coefficients	
Wind direction angle	0	Regional wind speed (V_R)m/s	48
Windward coefficient (C_p)	0.8	Terrain category	3
Leeward coefficient (C_p)	0.5	Directional multiplier (M_d)	1
Area reduction factor (K_a)	1	Shielding multiplier (M_s)	1
Combination factor (K_c)	1	Topographic multiplier (M_t)	1
Local pressure factor (KI)	1	Dynamic response factor (C_{dyn})	1
Porous Cladding factor (K_p)	1	Cyclone region	No

As explained in this section and Section 3.4, after applying all of the above forces and performing structural analysis, the D/C ratios (weighting factors) of all of the components of the bridge associated with each critical factor were calculated. The values shown in columns (v-ix) of Table 5-6 are the weighting factors respectively associated with live, flood, wind, earthquake, and collision. The values shown in column (i) of Table 5-6 are the current condition of the components, which are numbers from 1 to 5 and are obtained from inspection. The values of column (ii), which show the future condition of the components of the bridge, are numbers from 1 to 5 and calculated based on Markov Chain method. As explained in Section 3.5.1, the values of the column (i) and a transition probability matrix are used to calculate the values of the column (ii).

The values shown in column (iii) and (iv) of Table 5-6 respectively reflect the capacity loss of the components at the time of inspection and the future condition of the component (e.g. 5 years after inspection). These figures were calculated respectively by using the relevant values in columns (i) and (ii) and Table 3-10 and Table 3-21, and they are related to current and future capacities of the components.

Table 5-6 Current and future conditions of components and their weighting factors associated with different critical factors

Components	**CInsp (i)**	**CMav (ii)**	**CC (iii)**	**CF (iv)**	al_i **(v)**	afl_i **(vi)**	aw_i **(vii)**	ae_i **(viii)**	$acol_i$ **(ix)**
C1	1	2	105	118	0.56	0.87	0.34	0.38	>1
C11	2	3	118	134	0.56	0.87	0.34	0.38	>1
C12	2	3	118	134	0.56	0.87	0.34	0.38	>1
C13	1	2	105	118	0.56	0.87	0.34	0.38	>1
C2	2	3	118	134	0.5	0.87	0.32	0.38	>1
C21	2	3	118	134	0.5	0.87	0.32	0.38	>1
P1	1	2	105	118	0.68	0.53	0.43	0.4	0.5
P11	3	4	134	154	0.68	0.46	0.43	0.4	0.5
P2	2	3	118	134	0.68	0.52	0.42	0.4	0.5
P21	2	3	118	134	0.68	0.48	0.42	0.4	0.5
P3	1	2	105	118	0.68	0.51	0.42	0.4	0.5
P4	2	3	118	134	0.19	0.13	0.1	0.1	0.5
P41	1	2	105	118	0.19	0.11	0.1	0.1	0.5
P42	3	4	134	154	0.19	0.13	0.1	0.1	0.5
P43	2	3	118	134	0.19	0.11	0.1	0.1	0.5
P5	1	2	105	118	0.18	0.13	0.1	0.1	0.5
P51	1	2	105	118	0.18	0.11	0.1	0.1	0.5
P52	2	3	118	134	0.18	0.13	0.1	0.1	0.5
P53	1	2	105	118	0.18	0.11	0.1	0.1	0.5
P6	2	3	118	134	0.18	0.13	0.1	0.1	0.5
P61	2	3	118	134	0.18	0.13	0.1	0.1	0.5
Diaphragms Mid span	2	3	118	134	0.22	0.13	0.05	0.1	0.8

5.1.3 Step 3: Criticality and Vulnerability, Rating and Deadlines for Actions

The columns (i-vi) of Table 5-7 show the criticalities and vulnerabilities of the components of the bridge, and Table 5-8 shows the criticality and vulnerability of the bridge, calculated by using Eqs. 3.1 - 3.3, and deadlines for taking action based on Table 3-12, and Table 3-17 to Table 3-20.

Table 5-7 Criticality and vulnerability of the components

Components	**CCRLL (i)**	**CVRFl (ii)**	**CVRWd (iii)**	**CVREq (iv)**	**CVRCo (v)**	**CVREn (vi)**
C1	58.8	91.35	35.7	39.9	157.5	66.08
C11	66.08	102.66	40.12	44.84	177	75.04
C12	66.08	102.66	40.12	44.84	177	75.04
C13	58.8	91.35	35.7	39.9	157.5	66.08
C2	59	102.66	37.76	44.84	177	67
C21	59	102.66	37.76	44.84	177	67
P1	71.4	55.65	45.15	42	52.5	80.24
P11	91.12	61.64	57.62	53.6	67	104.72
P2	80.24	61.36	49.56	47.2	59	91.12
P21	80.24	56.64	49.56	47.2	59	91.12
P3	71.4	53.55	44.1	42	52.5	80.24
P4	22.42	15.34	11.8	11.8	59	25.46
P41	19.95	11.55	10.5	10.5	52.5	22.42
P42	25.46	17.42	13.4	13.4	67	29.26
P43	22.42	12.98	11.8	11.8	59	25.46
P5	18.9	13.65	10.5	10.5	52.5	21.24
P51	18.9	11.55	10.5	10.5	52.5	21.24
P52	21.24	15.34	11.8	11.8	59	24.12
P53	18.9	11.55	10.5	10.5	52.5	21.24
P6	21.24	15.34	11.8	11.8	59	24.12
P61	18.9	13.65	10.5	10.5	52.5	21.24
Diaphragm	23.1	13.65	5.25	10.5	84	25.96

Table 5-8 Criticality and vulnerability of bridge 1

		Inspection	**Structural Analyses**
B1-BCCR	475.795	Regular (every 2 years)	within 20 years
B1-BVRFl	503.45	Regular (every 2 years)	within 20 years
B1-BVRWd	287.875	Regular (every 2 years)	within 20 years
B1-BVREq	296.88	Regular (every 2 years)	within 20 years
B1-BVRCo	913	Within 1 months	within 3 months
B1-BVREn	539.12		
B1-BFCR	751.859		
B1-BOCR	635.972		

The costly part of the SRP is the calculation of weighting factors, presented for this example in Table 5-6. However, as explained in the method, this part is conducted once for each bridge and used for a long period as constant values by SRP. Every time the bridge is inspected by the inspector and CInsp values of Table 5-6 are updated, all values of Table 5-7 and Table 5-8 and column (ii) of the Table 5-6 will be instantly calculated through using SRP. The calculation of the importance of critical factors shown in Table 5-3 is also an easy task and can be accomplished by using inputs shown in Table 5-1, and the method explained in Section 3.3.3.

The values of column (i) of Table 5-7 show that the structure is capable of carrying live load, however, some of its components (e.g. p11, p2, and p21) are in critical condition. The CCRLL values associated with component p11 and its current condition suggest that by increasing the load by almost 10%, this component could fail due to live load. According to Table 3-11 this component should be replaced immediately. Table 5-7 shows that the CCRLL values of components p2 and p21 are equal to 80.24. According to Table 3-11 the criticality level of these components is CC3, hence, they should be inspected within 6 months and repaired in 1 year.

The CVRFl values associated with C11, C12, C2, and C21 show that if the structure is subjected to ULS flood load, these components will fail; therefore, the structure is vulnerable to severe flood. The CVRCo values associated with columns show those components that are vulnerable to collision. The reason is that the slender columns of this structure are exposed to vehicular impacts without any protection.

Therefore, protective components are required to be constructed to significantly reduce the vulnerability of the bridge to collision. CVRWd and CVREq values depict that none of the components of the bridge are vulnerable to wind and earthquake loads. The CVREn value associated with the components P11 shows that if no action is taken for this component within 5 years, the component is predicted to fail under the above live load.

In Table 5-7 CCRLL values show the criticality and rating of the components at the bridge and network level. CVRFl, CVRWd, CVREq and CVREn in that table show the vulnerability and rating of the components to different factors, and therefore the most vulnerable components within the network of railway bridges associated with each of critical factors can be identified.

The value of BFCR in Table 5-8 shows that if no action is taken, in 5 years the structure will be vulnerable towards the accumulative effects of critical factors. According to the values identified in Table 5-8, the rating of the criticality and vulnerability of the bridge among other bridges in the network will be identified, hence, engineers can identify the most damaged bridges or those bridges that are mostly prone to damage among other bridges for taking action. The actions that will be taken at the component level are repair and maintenance, but at bridge level the action is the reassessment of the safety and serviceability of the bridge by conducting structural analysis. The reliability of the weightings that will be calculated through structural analysis is high, and as a result, the most important decision (e.g. repair and maintenance) is made at the component level, where the weighting factors are directly used.

In this example the vulnerability of the bridge to some critical factors such as collision shows that although a particular bridge might not be vulnerable to some factors such as earthquake and wind, it could be very vulnerable to others. Therefore, it is very important to investigate the vulnerability of the structures and their components to different critical factors, and take action accordingly.

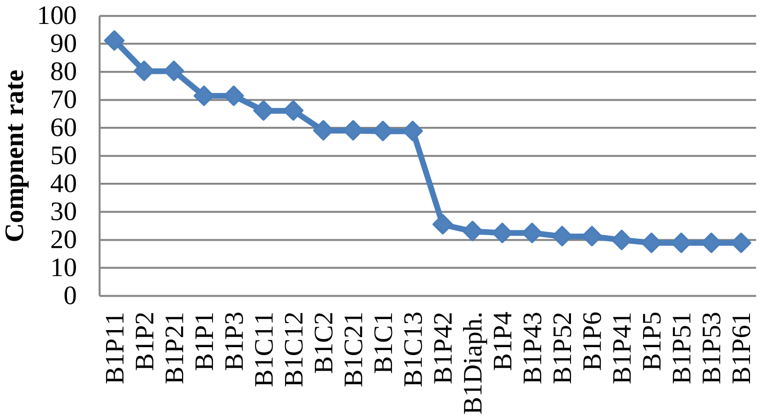
Table 5-9 and Table 5-10 show the deadlines for taking action for the components of the bridge. The deadlines are identified based on criticality and vulnerability of the components shown in Table 5-7 and criteria defined in Table 3-11, and Table 3-13 to Table 3-16. Figure 5-7 and Figure 5-8 show the rating of the components of the bridge at the network level.

Table 5-9 Deadlines for taking action on the components of bridge 1 associated with live, flood, and wind

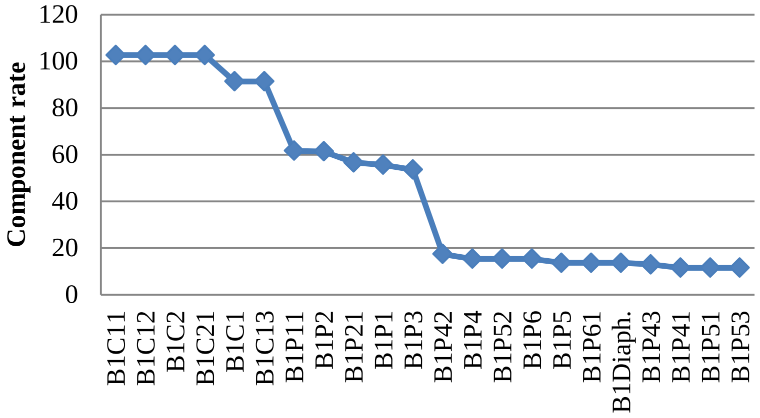
Component	Inspection (Live)	Repair and Maintenance (Live)	Inspection (Flood)	Repair and Maintenance (Flood)	Inspection (Wind)	Repair and Maintenance (Wind)
C1	Regular (every 2 years)	Not required	Bridge Closure	Immediate action	Regular (every 2 years)	Not required
C11	Regular (every 2 years)	Not required	Bridge Closure	Immediate action	Regular (every 2 years)	Not required
C12	Regular (every 2 years)	Not required	Bridge Closure	Immediate action	Regular (every 2 years)	Not required
C13	Regular (every 2 years)	Not required	Bridge Closure	Immediate action	Regular (every 2 years)	Not required
C2	Regular (every 2 years)	Not required	Bridge Closure	Immediate action	Regular (every 2 years)	Not required
C21	Regular (every 2 years)	Not required	Bridge Closure	Immediate action	Regular (every 2 years)	Not required
P1	Regular (every 2 years)	Not required	Regular (every 2 years)	Not required	Regular (every 2 years)	Not required
P11	Bridge Closure	Immediately Replaced	Regular (every 2 years)	Not required	Regular (every 2 years)	Not required
P2	Within 6 months	Repair in 1year	Regular (every 2 years)	Not required	Regular (every 2 years)	Not required
P21	Within 6 months	Repair in 1year	Regular (every 2 years)	Not required	Regular (every 2 years)	Not required
P3	Regular (every 2 years)	Not required	Regular (every 2 years)	Not required	Regular (every 2 years)	Not required
P4	Regular (every 2 years)	Not required	Regular (every 2 years)	Not required	Regular (every 2 years)	Not required
P41	Regular (every 2 years)	Not required	Regular (every 2 years)	Not required	Regular (every 2 years)	Not required
P42	Regular (every 2 years)	Not required	Regular (every 2 years)	Not required	Regular (every 2 years)	Not required
P43	Regular (every 2 years)	Not required	Regular (every 2 years)	Not required	Regular (every 2 years)	Not required
P5	Regular (every 2 years)	Not required	Regular (every 2 years)	Not required	Regular (every 2 years)	Not required
P51	Regular (every 2 years)	Not required	Regular (every 2 years)	Not required	Regular (every 2 years)	Not required
P52	Regular (every 2 years)	Not required	Regular (every 2 years)	Not required	Regular (every 2 years)	Not required
P53	Regular (every 2 years)	Not required	Regular (every 2 years)	Not required	Regular (every 2 years)	Not required
P6	Regular (every 2 years)	Not required	Regular (every 2 years)	Not required	Regular (every 2 years)	Not required
P61	Regular (every 2 years)	Not required	Regular (every 2 years)	Not required	Regular (every 2 years)	Not required
Diaphragms	Regular (every 2 years)	Not required	Regular (every 2 years)	Not required	Regular (every 2 years)	Not required

Table 5-10 Deadlines for taking action on the components of bridge 1 associated with earthquake and collision

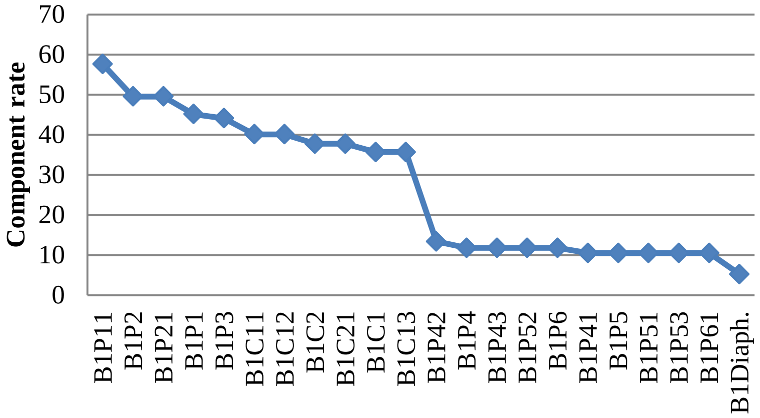
Component	**Inspection (Earthquake)**	**Repair and Maintenance (Earthquake)**	**Inspection (Collision)**	**Repair and Maintenance (Collision)**
C1	Regular (every 2 years)	Not required	Bridge Closure	Immediate action
C11	Regular (every 2 years)	Not required	Bridge Closure	Immediate action
C12	Regular (every 2 years)	Not required	Bridge Closure	Immediate action
C13	Regular (every 2 years)	Not required	Bridge Closure	Immediate action
C2	Regular (every 2 years)	Not required	Bridge Closure	Immediate action
C21	Regular (every 2 years)	Not required	Bridge Closure	Immediate action
P1	Regular (every 2 years)	Not required	Regular (every 2 years)	Not required
P11	Regular (every 2 years)	Not required	Regular (every 2 years)	Not required
P2	Regular (every 2 years)	Not required	Regular (every 2 years)	Not required
P21	Regular (every 2 years)	Not required	Regular (every 2 years)	Not required
P3	Regular (every 2 years)	Not required	Regular (every 2 years)	Not required
P4	Regular (every 2 years)	Not required	Regular (every 2 years)	Not required
P41	Regular (every 2 years)	Not required	Regular (every 2 years)	Not required
P42	Regular (every 2 years)	Not required	Regular (every 2 years)	Not required
P43	Regular (every 2 years)	Not required	Regular (every 2 years)	Not required
P5	Regular (every 2 years)	Not required	Regular (every 2 years)	Not required
P51	Regular (every 2 years)	Not required	Regular (every 2 years)	Not required
P52	Regular (every 2 years)	Not required	Regular (every 2 years)	Not required
P53	Regular (every 2 years)	Not required	Regular (every 2 years)	Not required
P6	Regular (every 2 years)	Not required	Regular (every 2 years)	Not required
P61	Regular (every 2 years)	Not required	Regular (every 2 years)	Not required
Diaphragms	Regular (every 2 years)	Not required	Within 6 months	Repair in 1year



a) Rating of components associated with live load

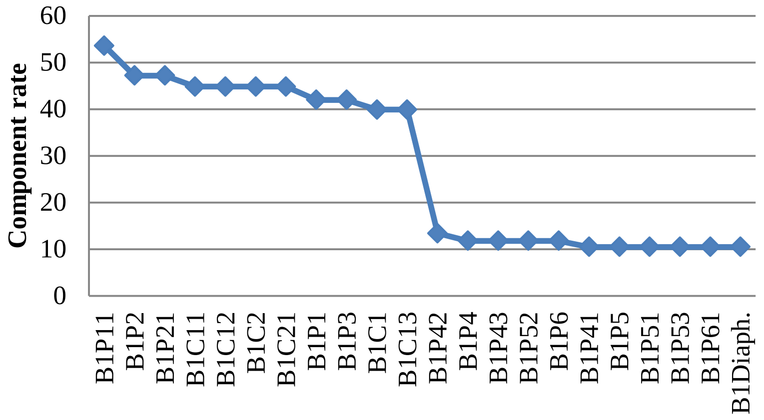


b) Rating of components associated with flood

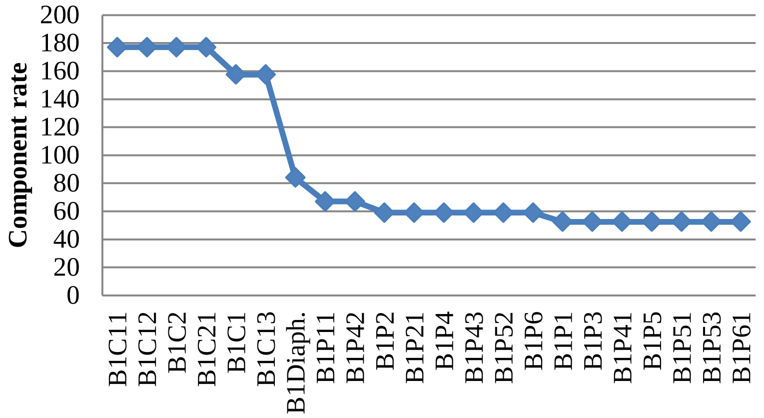


c) Rating of components associated with wind

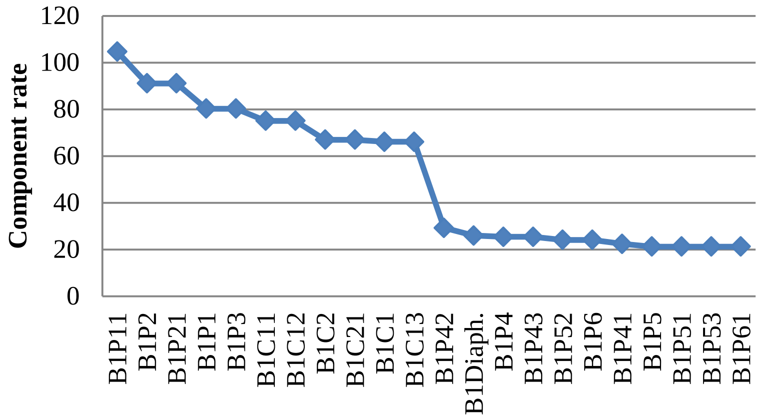
Figure 5-7 Rating of the components of bridge 1 to live, flood, and wind



a) Rating of components associated with earthquake



b) Rating of components associated with collision



c) Rating of components associated with environment

Figure 5-8 Rating of the components of bridge 1 to earthquake, collision and environment

5.2 BRIDGE 2

5.2.1 Step 1: Contribution of Critical Factors towards Bridge Deterioration

Figure 5-9 shows the structure of a railway bridge used in this example. The bridge is located in Australia. The structure is prone to train, flood, wind, and earthquake loads, and its condition degrades due to environmental effects.

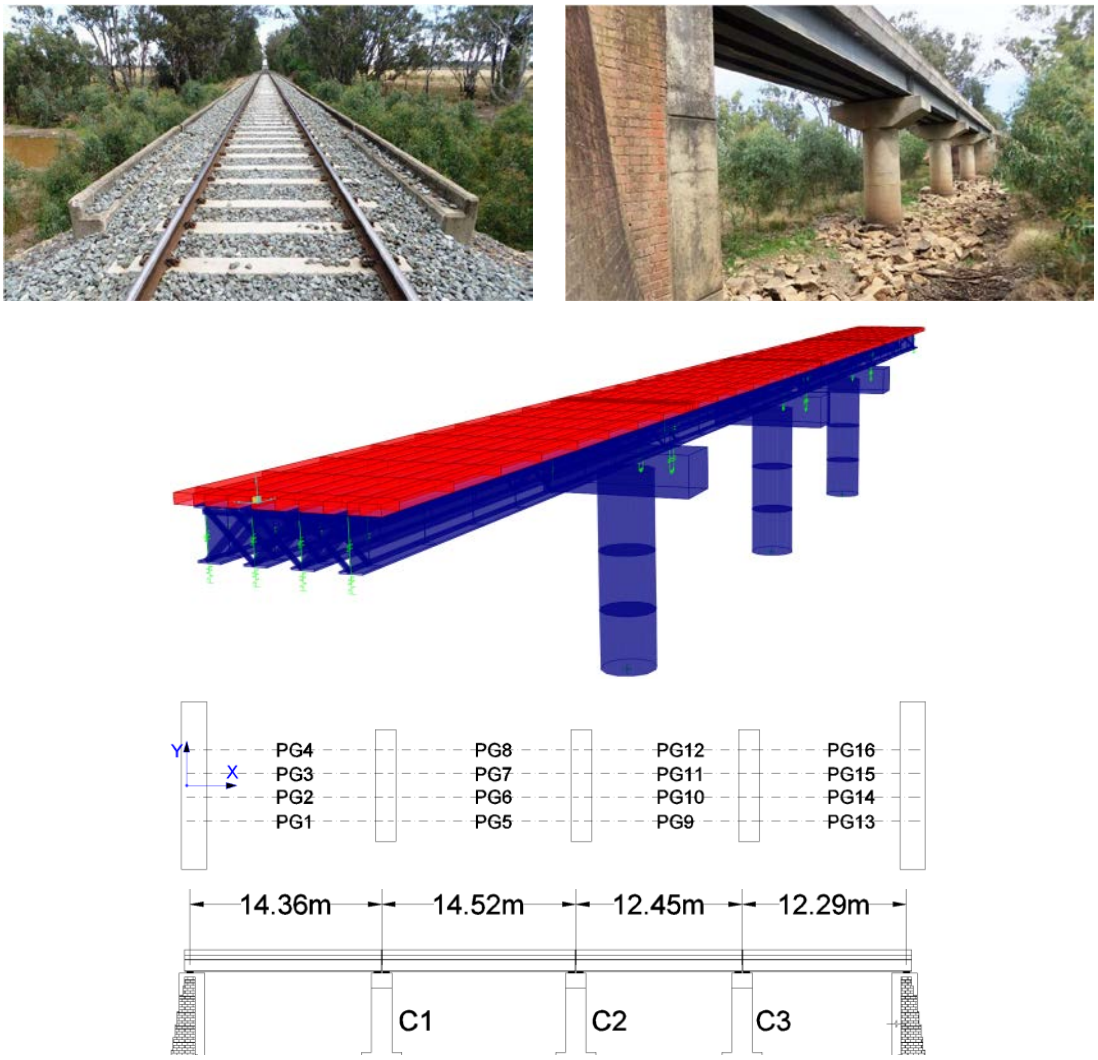


Figure 5-9 Geometry of the railway bridge structure

Table 5-11 shows the risks associated with each critical factor. The importance of critical factors is determined by utilizing the method introduced in Section 3.3. *A2* is the pair-wise comparison between factors. Table 5-12 shows the criticality coefficient of each factor and Table 5-13 shows the contribution of each critical factor towards bridge deterioration. The values of Table 5-13 are used to calculate the future condition of the bridge (BFCR).

Table 5-11 The risk associated with the critical factors related to railway bridge 2

Environmental condition:	B
ARI (AS5100.2, 2004)	100
Wind (AS1170.2, 2002)	A1
Z (AS1170.4, 2007)	0.09
K_p (AS1170.4, 2007)	1.3
Traffic volume	D
Cm1 to Cm10	1

Table 5-12 Calculation of the coefficients

C_{ev}	1.5
C_{fl}	1.65051
C_{w}	1
C_{eq}	1.56

$$A2 = \begin{array}{c} \\ Ev \\ Fl \\ W \\ Eq \end{array} \begin{array}{c} \begin{array}{cccc} Ev & Fl & W & Eq \end{array} \\ \begin{bmatrix} 1 & 3.398939 & 1122 & 719.2308 \\ 0.294209 & 1 & 330.103 & 211.6045 \\ 0.000891 & 0.003029 & 1 & 0.641026 \\ 0.00139 & 0.004726 & 1.56 & 1 \end{bmatrix} \end{array}$$

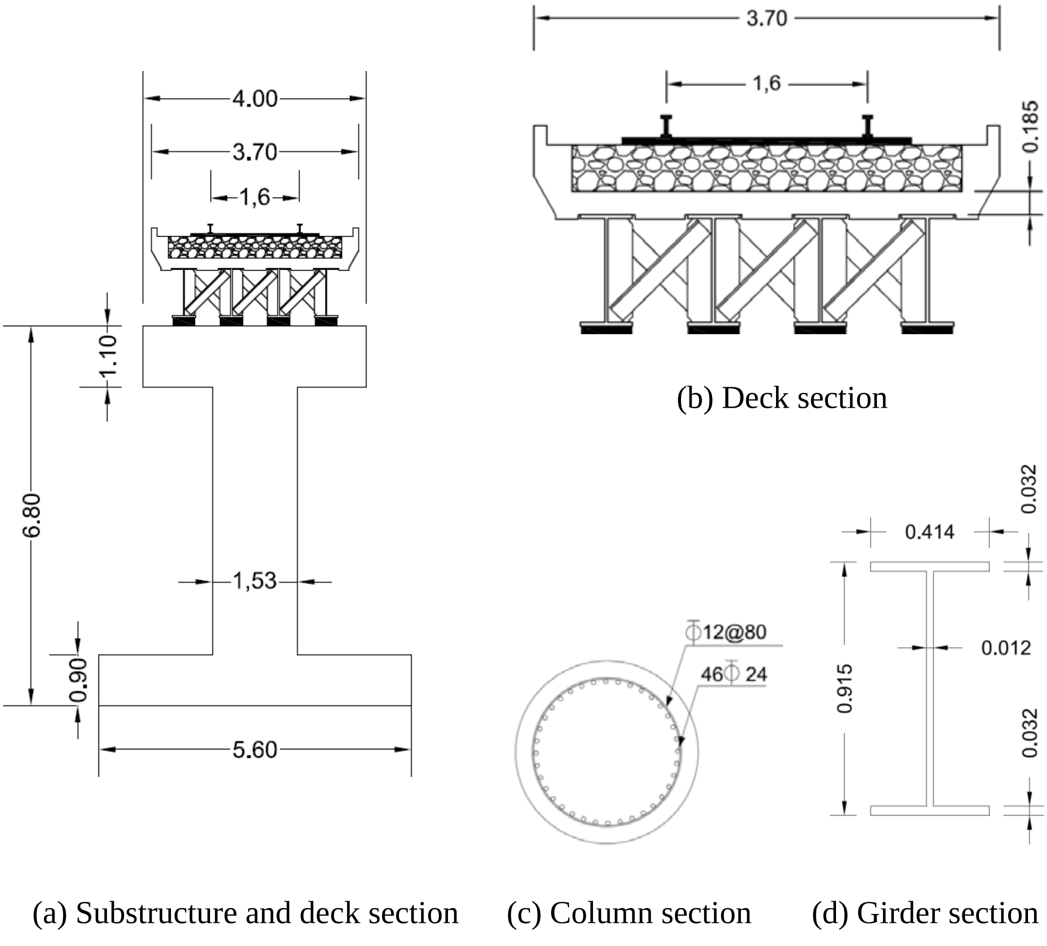
Table 5-13 Contribution of the critical factors towards bridge deterioration

β_{ev}	0.95934
α_{fl}	0.282247
α_{w}	0.000855
α_{e}	0.001334

5.2.2 Step 2: Weighting Factors of each Component of a Bridge Associated with Different Critical Factors.

As explained before, D/C ratios of the structural components of the bridge prone to different critical factors are calculated based on structural analysis and used as their weighting. The weighing factors are related to the safety level, hence ULS critical forces are applied to the structure to calculate D/C ratios. It has been assumed that the components of the bridge have lost almost 30% of their capacities.

Live load: The load combination applied to the bridge is 1.2 Dead + 3.5 Live. The live load is an N class train load shown in Figure 4-2. The speed of the train is 100 km/hr. The cross section of columns (C1, C2 and C3), plate girders (PG1 to PG16) and the deck are shown in Figure 5-10. The values shown in Figure 5-10 are all in meter.

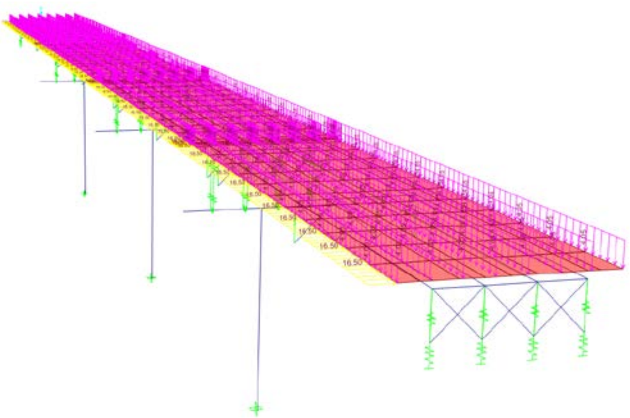


(b) Deck section

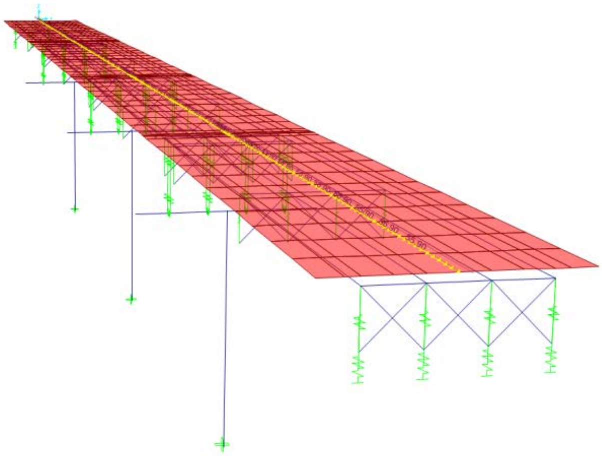
(a) Substructure and deck section (c) Column section (d) Girder section

Figure 5-10 Details of the structure

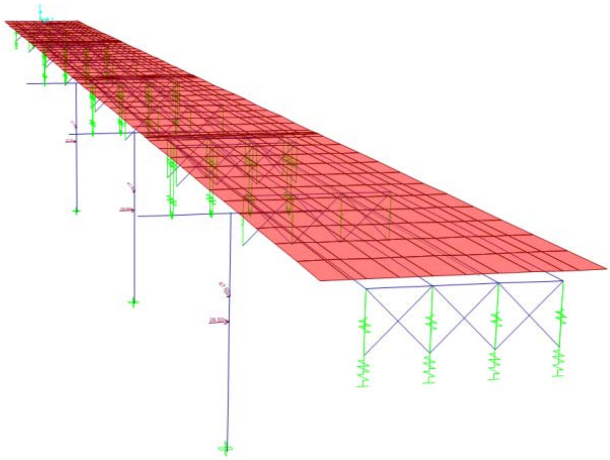
Flood: Figure 5-11 shows the flood forces applied to the structure. These forces were calculated based on AS 5100.2 (2004). At ultimate limit state it is assumed that the flood level would be about 3 m above the track. The load combination applied to the bridge is 1.2 Dead + 1.7 Flood.



(a) Forces on superstructure (4.05 kN/m^2 downward and 16.5 kN/m drag force)



(b) Forces on superstructure (55.9 kNm/m moment force)



(c) Forces on substructure (on each pier, 47.6 kN in longitudinal and 28.5 kN in transverse directions)

Figure 5-11 Flood forced applied on the sub and superstructure of the bridge

Earthquake: Table 5-14 shows the parameters considered for response spectrum function and Figure 5-12 shows the response spectrum function applied to the structure based on AS 1170.4 (2007).

Table 5-14 Response spectrum function definition (AS1170.4, 2007)

Site subsoil class	C
Probability factor (Kp)	1.3
Hazard factor (Z)	0.09
Structural performance factor (Sp)	0.77
Function damping ratio	0.05

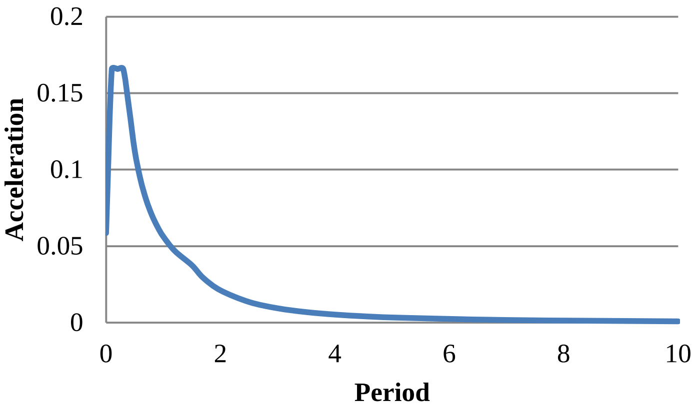


Figure 5-12 Response spectrum function (AS1170.4, 2007)

For column pushover analysis performed to calculate the demand/capacity ratios, demand by capacity ratios for columns were calculated based on deflections and considering the plastic capacity of the bridge. However, for beams 1.2 × Dead load was considered to calculate the demand by capacity ratios of the components based on internal stresses in the components, without taking into account the seismic effects. In identifying the D/C ratios of components associated with earthquake, 1.2 × Dead load was considered as the weight of the bridge.

Wind: Regional basic design wind speed for a 2000 year average return interval and for region A1 is obtained from AS/NZS 1170.2-2002, which is equal to V_{2000}= 48 m/s. All other parameters are shown in Table 5-15. The wind load is applied to the structure when a train with the height of 3.625 meters is passing over the bridge. To calculate the D/C ratios of the components associated with wind, 1.2 Dead + Wind is taken into account.

Table 5-15 Wind exposure parameters and wind coefficients

Wind exposure parameters		Wind coefficients	
Wind direction angle	0	Regional wind speed (V_R)m/s	48
Windward coefficient (C_p)	0.8	Terrain category	2
Leeward coefficient (C_p)	0.5	Directional multiplier (M_d)	1
Area reduction factor (K_a)	1	Shielding multiplier (M_s)	1
Combination factor (K_c)	1	Topographic multiplier (M_t)	1
Local pressure factor (KI)	1	Dynamic response factor (C_{dyn})	1
Porous Cladding factor (K_p)	1	Cyclone region	No

5.2.3 Step 3: Criticality and Vulnerability, Rating and Deadlines for Actions

Table 5-16 shows the current condition of the components obtained from inspection, future condition of the component, and the weighting factors associated with each critical factor. Table 5-17 shows the criticalities and vulnerabilities of the components. The conditions of the components (CInsp) in Table 5-16 are assigned to be different from the real condition of the components, in order to illustrate the method more clearly. The future condition of the components (e.g. after 5 years) shown in column (ii) of Table 5-16, are calculated based on the Markov chain method. The weighing factors shown in columns (v) to (viii) in Table 5-16, are the D/C ratios of the components, and they were calculated based on the structural analyses explained in previous section. The bridge would not be subjected to vehicular impact, so the contribution of collision is zero. Columns (i-v) of Table 5-17 show the criticality and vulnerability of the components of the bridge, and Table 5-18 shows the criticality and vulnerability of the bridge, calculated based on synthetic rating equations.

Table 5-16 Current and future condition of components and their weighting factors associated with different critical factors

Components	**C Insp (i)**	**C Mav (ii)**	**CC (iii)**	**CF (iv)**	al_i **(v)**	afl_i **(vi)**	aw_i **(vii)**	ae_i **(viii)**
C1	1	2	105	118	0.5	0.44	0.15	0.38
C2	2	3	118	134	0.5	0.44	0.15	0.38
C3	2	3	118	134	0.5	0.44	0.15	0.38
PG1	1	2	105	118	0.59	0.42	0.12	0.12
PG2	2	3	118	134	0.59	0.29	0.12	0.12
PG3	2	3	118	134	0.59	0.15	0.12	0.12
PG4	1	2	105	118	0.59	0.33	0.12	0.12
PG5	3	4	134	154	0.59	0.41	0.12	0.12
PG6	2	3	118	134	0.59	0.26	0.12	0.12
PG7	2	3	118	134	0.59	0.16	0.12	0.12
PG8	1	2	105	118	0.59	0.3	0.12	0.12
PG9	2	3	118	134	0.61	0.32	0.09	0.09
PG10	1	2	105	118	0.61	0.22	0.09	0.09
PG11	3	4	134	154	0.61	0.1	0.09	0.09
PG12	2	3	118	134	0.61	0.21	0.09	0.09
PG13	1	2	105	118	0.49	0.32	0.09	0.09
PG14	1	2	105	118	0.49	0.1	0.09	0.09
PG15	2	3	118	134	0.49	0.22	0.09	0.09
PG16	1	2	105	118	0.49	0.21	0.09	0.09
Diaphragm	2	3	118	134	0.1	0.24	0.1	0.1

Table 5-17 Criticality and vulnerability of the components

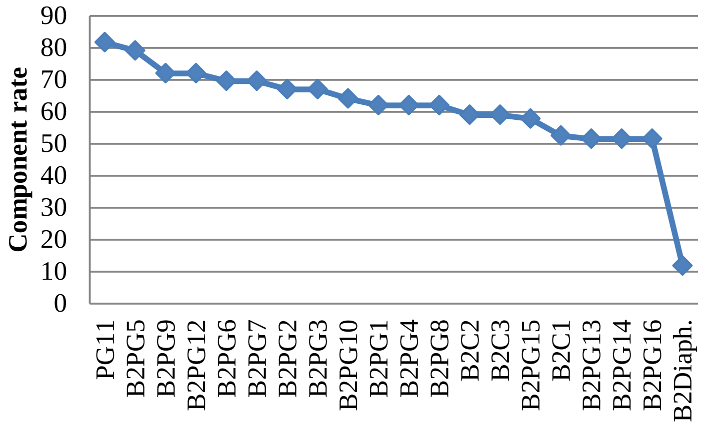
Components	CCRLL (i)	CVRFl (ii)	CVRWd (iii)	CVREq (iv)	CVREn (v)
C1	52.5	46.2	15.8	39.9	59
C2	59	51.9	17.7	44.8	67
C3	59	51.9	17.7	44.8	67
PG1	62	44.1	12.6	12.6	69.6
PG2	67	34.2	14.2	14.2	79.1
PG3	67	17.7	14.2	14.2	79.1
PG4	62	34.7	12.6	12.6	69.6
PG5	79.1	54.9	16.1	16.1	90.9
PG6	69.6	30.7	14.2	14.2	79.1
PG7	69.6	18.9	14.2	14.2	79.1
PG8	62	31.5	12.6	12.6	69.6
PG9	72	37.8	10.6	10.6	81.7
PG10	64.1	23.1	9.5	9.5	72
PG11	81.7	13.4	12.1	12.1	93.9
PG12	72	24.8	10.6	10.6	81.7
PG13	51.5	33.6	9.5	9.5	57.8
PG14	51.5	10.5	9.5	9.5	57.8
PG15	57.8	26	10.6	10.6	65.7
PG16	51.5	22.1	9.5	9.5	57.8
Diaphragm	11.8	28.3	11.8	11.8	13.4

Table 5-18 Criticality and vulnerability of the bridge

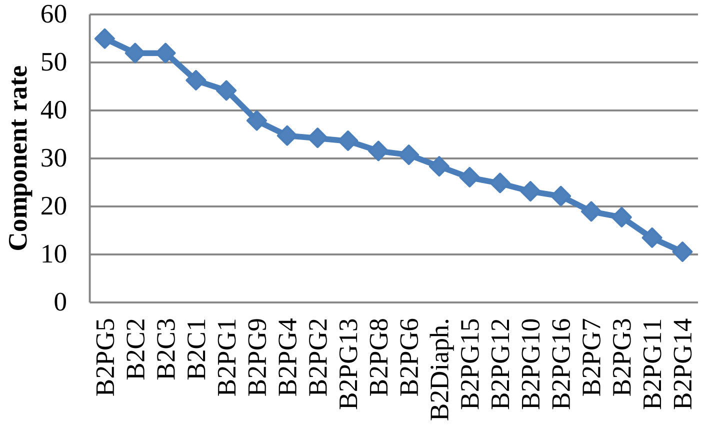
BOCR	647.3396
BCCR	613.805
BFCR	757.2753
BVRFl	318.09
BVRWd	127.595
BVREq	166.81
BVREn	695.44

In Table 5-16 the weighting factors related to live load (al_i) for some girders are higher than columns, because the columns of this bridge are assigned safety factors higher than beams. Table 5-17 shows the level of criticality of all components (CCRLL) except that PG5 and PG11 are less than 75 and it means that according to Table 3-11 the level of their criticality is CC1. Based on Table 5-17 and Table 3-11, the criticality of the PG5 and PG11 are CC2 and CC3 respectively. According to Table 3-11, PG5 should be inspected in 1 year and PG11 should be inspected in 6 months and repaired in 1 year. The last column of Table 5-17 shows the conditions of the components in the future. These conditions not only show the extent of damage in the components due to environmental effects and fatigue, but also take into account the criticality of the component.

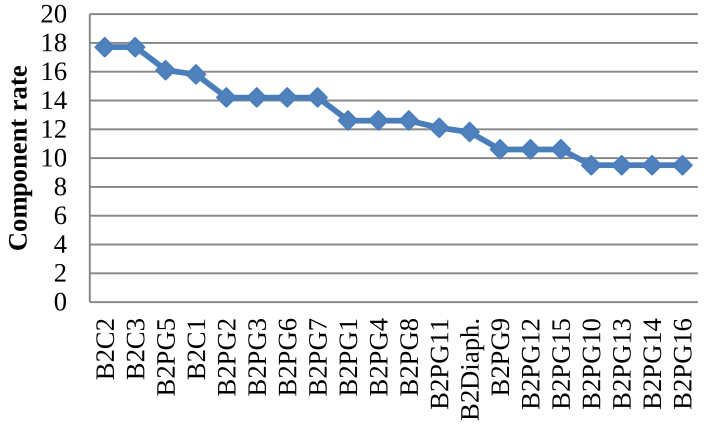
CCRLL values of Table 5-17 show the criticality and rating of the components at the bridge and network level associated with live load. In Table 5-17, CVRFl, CVRWd, CVREq and CVREn values show the vulnerabilities and ratings of the components to different factors, therefore, the most vulnerable components within the network of bridges to each of critical factors can be identified. The ratings of the components related to different critical factors at the bridge level are also shown in Figure 5-13 and Figure 5-14. In this example, none of the components was vulnerable to any of critical factors at the time. According to Table 5-18, the structure was not vulnerable to any extreme event at the time, and it was not in the critical condition for carrying train loads. However, taking into account all critical factors, including extreme events and environmental and fatigue, the future condition of the bridge (BFCR) (e.g. after 5 years), would be at the second level of vulnerability. According to the values identified in Table 5-18, the rating of the criticality and vulnerability of the bridge among other bridges in the network would be identified, and hence, the engineers could identify the most damaged bridges or those bridges which were mostly prone to damage among other bridges. Based on Table 5-18 the deadlines for performing structural analyses would be identified. By using Eq. 3.21 γ_2 would be calculated as 0.23, which means that the condition of a bridge within a specific period (e.g. 5 years for this example) deteriorates by 23%. The value of γ_2 assists engineers to anticipate the rate of the bridge deterioration.



a) Rating of components associated with live load

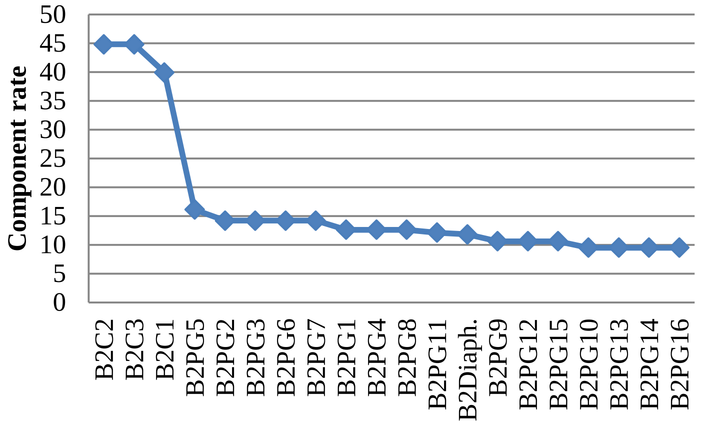


b) Rating of components associated with flood

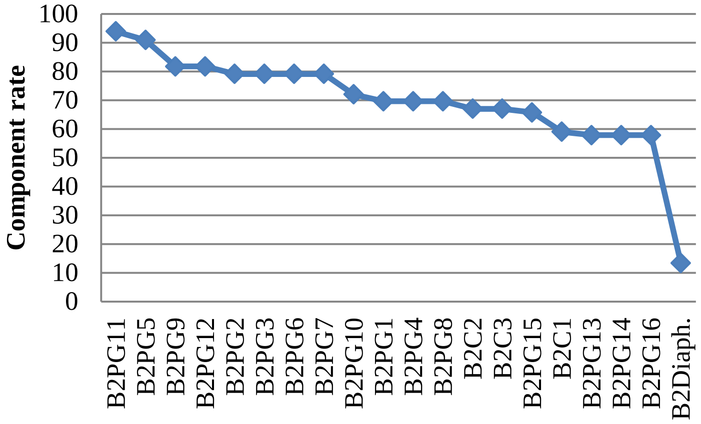


c) Rating of components associated with wind

Figure 5-13 Rating of the components of bridge 2 to live, flood and wind



a) Rating of components associated with earthquake



b) Rating of components associated with environment

Figure 5-14 Rating of the components of bridge 2 to earthquake and environment

5.3 CRITICALITIES, VULNERABILITIES AND RATINGS OF ALL COMPONENTS OF NETWORK BRIDGES

Figure 5-15 to Figure 5-20 show the ratings of the components of a network of railway bridges including bridges 1 and 2. In these figures, B1 identifies components of bridge 1, and B2 identifies components of bridge 2. Figure 5-15 shows the most critical component (B1Pll) belongs to bridge 1. Figure 5-16 shows that almost all of the columns of bridge 1 were vulnerable to a severe flood. However, these components could carry the live load with the acceptable level of safety. This information about the columns of bridge 1 suggests that the columns were vulnerable to significant lateral loads. Therefore, two retrofitting methods could be considered. The first one would be to increase the flexural capacity of the columns and the second method would be to add lateral resisting components such as bracing to the structure. If these columns were vulnerable to vertical loads, the first method of retrofitting could be more economical. However, for this structure adding bracing components in the direction of the water flow would be more applicable. Figure 5-17, and Figure 5-18 show that the columns mentioned above were among components that showed the highest vulnerabilities to wind and earthquake, although neither of the structures was vulnerable to wind and earthquake as these loads were not high. Therefore, using bracing or shear walls could improve the behaviour of the structure to lateral loads. Figure 5-19 shows that the columns of bridge 1 were very vulnerable to collision, therefore, by adding protective components around the columns the structure would be protected from vehicular impact.

From the above interpretation of the data in Figure 5-15 to Figure 5-20, it can be observed that the rating numbers not only identified the worst components, but could also assist engineers to identify the type of action necessary, as the rating values have meaning for structural engineers. In addition, it can be concluded that if some components were identified as vulnerable components, straightening them would not be the only option. As can be seen from the above example, to improve the safety of the bridge 1, it would be more practical, and perhaps economical, to add bracing to the structure rather than straightening the columns. Identifying different ratings for each component based on the vulnerabilities of the component to different critical factors, or criticalities of the components to live load, assists engineers to determine the best repair actions. As can be observed, each of the Figure 5-15 to Figure 5-20 suggests different type of repair actions. Figure 5-20 shows the future condition of the components of the bridges if no extreme events occurred for 5 years. By comparing Figure 5-15 with Figure 5-20, it identified that within 5 years almost 8 components would be added to the components with the rating values above 80. Therefore, the figures provide indications about the rate of deterioration.

Figures 5-21 (a) and (b) show the values of the ratings of bridges associated with their current and future conditions. The future condition in Figure 5-21 (b) encompasses all critical factors including extreme events and environment. As shown in Figure 5-21 (a), the rating value related to the current condition of bridge 1 is equal to 475.795, and bridge 2 is equal to 613.805. Figure 5-21 (b) shows the rating values of 751.859 and 757.275 which are respectively related to bridge 1 and bridge 2. As can be seen the current condition of the bridge 1 is considerably better than bridge 2. However, the values of ratings associated with the future condition of both bridges show that they would have a similar condition in future. This means that bridge 1 is more vulnerable to critical factors than bridge 2. Figure 5-21 (c-f) shows the higher vulnerabilities of bridge 1 to all critical factors compared to bridge 2. This indicates that taking protective action for bridge 1 is more important than bridge 2, although the current condition of the bridge 1 is better.

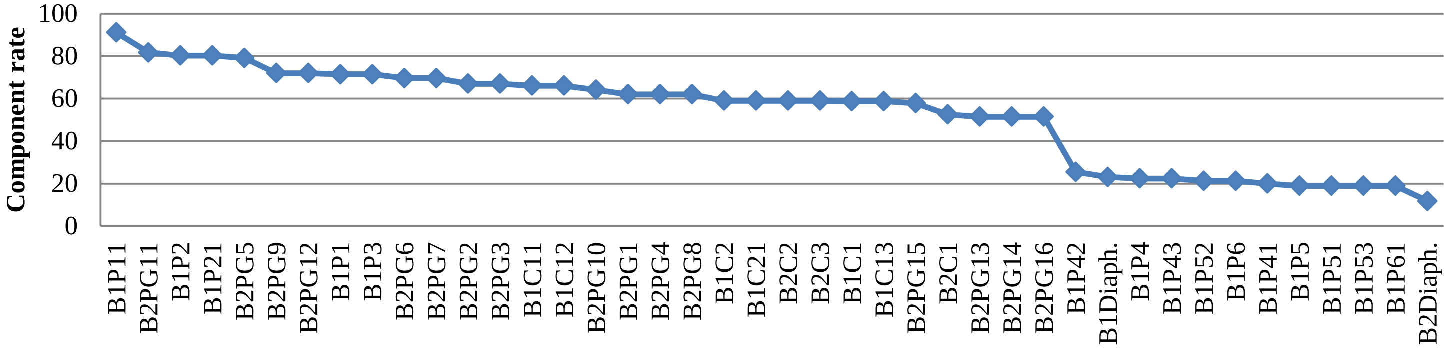


Figure 5-15 Rating of components of the network of two bridges associated with live load

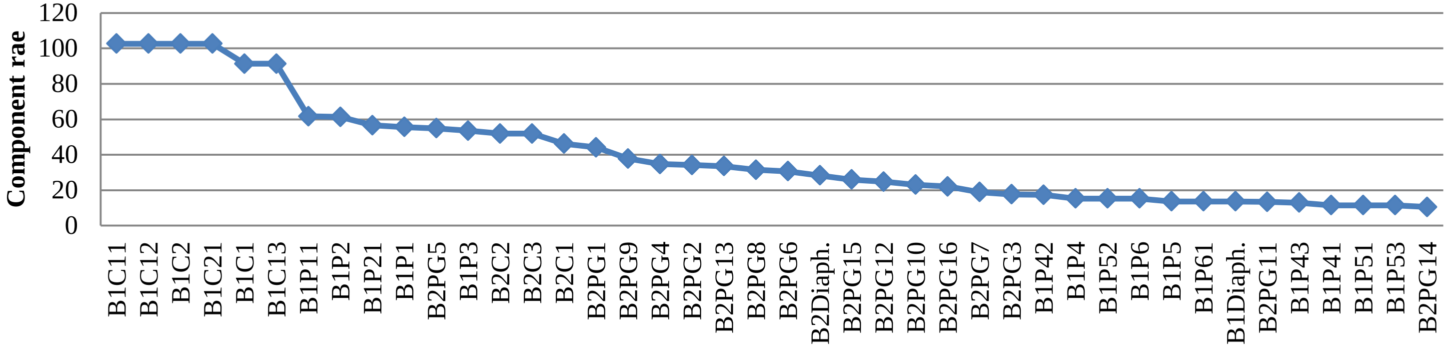


Figure 5-16 Rating of components of the network of two bridges associated with flood

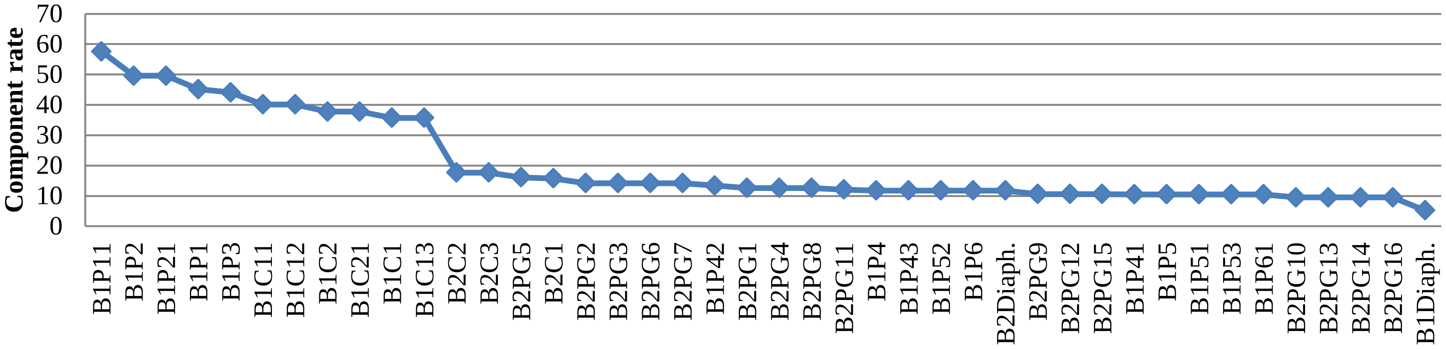


Figure 5-17 Rating of components of the network of two bridges associated with wind

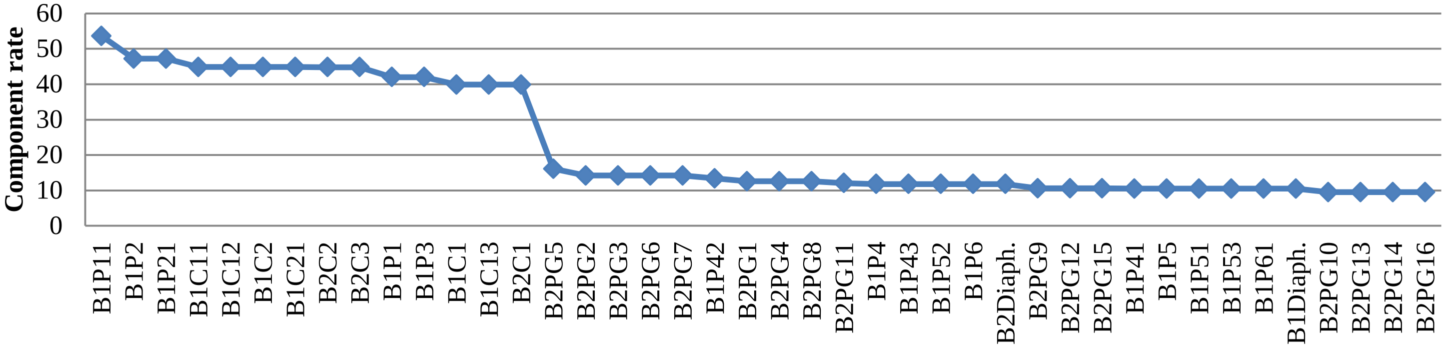


Figure 5-18 Rating of components of the network of two bridges associated with earthquake

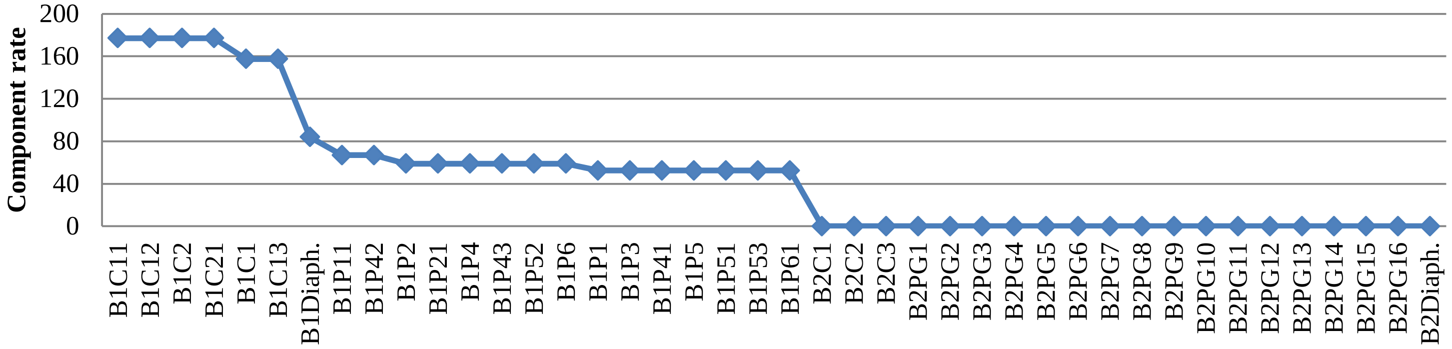


Figure 5-19 Rating of components of the network of two bridges associated with collision

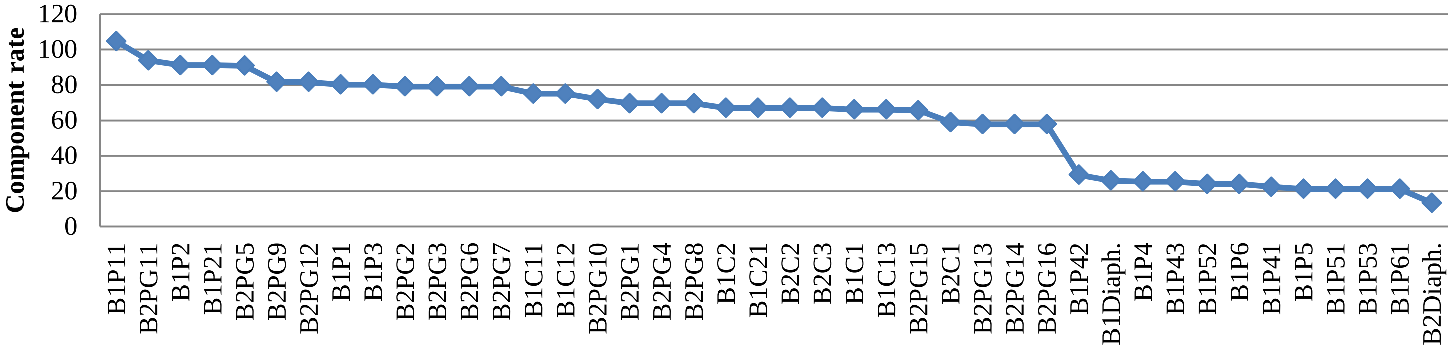


Figure 5-20 Rating of components of the network of two bridges associated with environment

(a) Rating values related to the current condition of bridges (BCCR)

(b) Rating values related to the future condition of bridges (BFCR)

(c) Rating values of bridges associated with the wind (BVRWd)

(d) Rating values of bridges associated with the earthquake (BVREq)

(e) Rating values of bridges associated with the flood (BVRFl)

(f) Rating values of bridges associated with the collision (BVRCo)

Figure 5-21 Rating values of bridges associated with current and future condtions and each critical factor

5.4 COMPARISON WITH CURRENT RATING METHODS

Numerous rating methods are used in Australia and different countries as discussed in Chapter 2. Taking into account that the current rating systems are very different and subjective, makes the comparison of this method with other rating methods through quantifying their reliability and practicality impossible. For instance, in the current existing rating systems that can be applied to a network of bridges, the current practices consider different ranges of numbers (e.g. 1-5, 1-10, 1-4 etc.) or even descriptive information to describe the condition of the components. When the existing rating methods assess the condition of bridges, they do not conduct structural analysis or use measurable tools such as an appropriate SHM system, hence, their results are not scientifically and reliably measurable. For those methods that can only be applied to one important bridge, although their results are reliable, they cannot be applied to a network of bridges as they are very costly. Therefore, in this research efforts were made to elaborate the advantages of the developed rating method over other existing rating methods through discussion in different parts of developing the method and explaining its philosophy.

The discussions will focus on the sources of subjectivity, how reliable tools such as structural analysis and appropriate SHM systems are selected among others and how they can be incorporated into the newly developed rating methods to reduce the subjectivity. In this method, contrary to current existing methods that can be applied to a network of bridges, the main decisions for conducting the repair and maintenance of components will be made based on the results of structural analysis and design, hence, this method is scientifically measurable.

In comparison to the reliable methods that can only be applied to one important single bridge, the proposed method only avoids conducting costly structural analysis methods such as alternative load path, or performing more detailed structural assessment by adopting SHM systems. Therefore, considering that for the majority of the railway bridges that have simple structures, the above detailed structural evaluations are not necessary, the above strategy will help to enhance the practicality of the method to be applied to a network of bridges, and the results of the proposed method will be similar to a sophisticated method. As previously mentioned, for important railway bridges with complex structures, their assessments were outside of the scope of this research as their numbers in a network of bridges were minimal and more sophisticated methods might be required. Therefore, their condition assessments and ratings, and allocation of their budgets can be separately conducted.

The practicality of the developed method in this research was also evaluated based on assessing the capabilities of current existing BMSs in Australia (the industry partners of the main project of this research) and other countries. The common sources of subjectivity were identified in this research by criticality reviewing the literature and interviewing the experts of the industry partners of the main project (LCMRB) in charge of repair and maintenance of more than a thousand railway bridges in Australia. The available knowledge and appropriate tools, such as Analytic Hierarchy Process (AHP), structural analysis, and available risk assessment in design standards were also selected to be used in this method by conducting a comprehensive literature review and comparing the advantages and disadvantages of these selected tools in respect to others.

As an example, to briefly illustrate the advantages of the proposed synthetic rating method, it will be compared with some rating methods which are used in Australia (e.g. VicRoads, DMR Qld and RMS NSW) (Austroads, 2004). According to VicRoads (Austroads, 2004), the criticality rating (CR) for each component is calculated based on the material and the structural group that the component belongs to. CR varies from 1 to 12, and higher values of CR show the higher criticality of the components. CR in VicRoads is equivalent to the weighting factor term that is used in this research. Table 5-19 shows the weighing factors (CR as in VicRoads) that are calculated for each component of Bridge 1. The CR values are the same for all components of the same type and same material for all bridges with different structural geometries and ages. CR values also do not change when the structure is subjected to different loads. As can be observed, compared to the weighting factors shown in columns v to ix of Table 5-6 that were calculated based on the synthetic rating method, the VicRoads weighting factors do not take into account,

1) The contribution of different critical factors to bridge deterioration,
2) The D/C ratios of the components when they are subjected to different loads,
3) The vulnerability of the components to different critical factors, or
4) The section properties of different components, and the geometry of different structures.

Therefore, rating of components and identifying the components in most need of repair cannot be conducted in a reliable way and appropriate remedial actions associated with different critical factors cannot be determined. According to VicRoads, the condition of the bridge is calculated based on the above weighting factors (CR), hence, the condition of the bridge will be predicted in a very subjective way. Other BMSs such as DMR Qld and RMS NSW (Austroads, 2004), have the same problems as mentioned above.

Similar comparisons between the rating method developed in this research and other rating methods used in Australia show the incomparable reliability of the present synthetic rating method to others. The synthetic rating method involves structural analysis and SHM systems in the condition assessment process in a practical way, and uses data in BMS to evaluate the contribution of different critical factors towards bridge deterioration. As mentioned previously, based on the comprehensive review of the literature conducted in this research, the same gaps as mentioned above are common among available rating systems used in practice throughout the world, and the proposed method can fill these gaps in a practical and reliable way.

Table 5-19 Criticality Rating (CR) (as weighting factors in this thesis) of components of Bridge 1

Components	**CInsp (i)**	**Structural Group**		**Material**		**CR**
		Substructure	Superstructure	**Steel**	**Cast in-situ Concrete**	
C1	1	3			3	9
C11	2	3			3	9
C12	2	3			3	9
C13	1	3			3	9
C2	2	3			3	9
C21	2	3			3	9
P1	1		3	1		3
P11	3		3	1		3
P2	2		3	1		3
P21	2		3	1		3
P3	1		3	1		3
P4	2		3	1		3
P41	1		3	1		3
P42	3		3	1		3
P43	2		3	1		3
P5	1		3	1		3
P51	1		3	1		3
P52	2		3	1		3
P53	1		3	1		3
P6	2		3	1		3
P61	2		3	1		3
Diaphragms Mid span	2		3	1		3

5.5 CONCLUDING REMARKS

This chapter illustrated the application of the SRP on a network of two bridges. The number of bridges and their components in the network could be any and there is no limit on this. For the above two bridges, the importance of critical factors was identified, the weighting factors of the components calculated, and the criticality and vulnerability of the components evaluated. The ratings of the components at bridge and network level were shown in tables and figures. The required actions for components and bridges based on the results of SRP were identified. The results were discussed for further illustration of the method.

According to the results obtained in this section, it can be concluded that, by using the synthetic rating method and its procedures, and contrary to current practical rating methods, engineers can identify the effect of any damage in any component of the bridge on the whole structure by performing structural analyses. For important bridges, the condition of the components and their performance can be monitored using SHM sensors, and the results can be used as weighting factors of components in the synthetic rating method. In addition, the method can reliably determine the most critical and vulnerable components and most damaged structures at the network level and deadlines for taking action. This information about the current and future conditions of the components and bridges and deadlines for taking action is extremely important for identifying the best time for intervention. The best time for intervention before the identified deadlines based on SRP will be calculated after taking into account other non-structural factors such as cost, human and social factors and through prioritization and optimization processes in BMS.

Chapter 6: Conclusions and Future Work

The condition of a railway bridge deteriorates with age due to the effects of critical factors such as environment, fatigue and extreme events. In order to maintain the safety and serviceability of railway bridges, engineers should assess their condition, estimate their durability and recommend appropriate repair and maintenance actions. Current practice for determining the most damaged bridges in a network of bridges and rating them based on their structural condition is too subjective. This subjectivity comes from simplifying a very complex system to make it practical enough to be applied to thousands of bridges. The current condition assessment methods used in practice are simple, however, due to their shortcomings and subjectivity, they are not fully applied in real practice.

The category of current more reliable methods, based on criticality and vulnerability analysis, can only be applied to one particular bridge, as they are sophisticated and costly. Therefore, a practical rating method was needed to be developed to reliably identify the bridges in the worst condition among all bridges in a network.

6.1 CONCLUSIONS

As mentioned above, developing a new method of rating which can identify the bridges in the worst condition among all bridges in a network is essential, as it assists managers to efficiently invest scarce resources on those bridges in most need of repair. The reliability and practicality of the current existing methods are not scientifically measurable, as they are numerous, very different and very subjective. Therefore, the reasons that demonstrate why the method proposed in this research is practical and more reliable than current methods have been elaborated through discussions throughout the previous chapters of this thesis. This chapter outlines a summary of those discussions and includes concluding remarks. In order to develop a practical and reliable rating system, the following steps have been taken in this research.

a) Literature review

This research reviewed the literature on different stages of bridge condition assessment including inspection, structural condition evaluation, and rating bridges, to develop a rating method that is more reliable than the conventional existing practical methods currently used for rating a network of railway bridges. Within the inspection process, the following shortcomings were identified:

1. There are vast uncertainties in the results of different inspection techniques such as visual and NDT methods;
2. The most appropriate time to apply the more expensive methods or systems such as NDT or SHM, which can be more reliable than others such as visual inspection, is unknown;
3. Resources are inefficiently invested by increasing the inspection intervals on unnecessary components;
4. Not appropriately focusing on the critical or vulnerable components of the bridge.

The high subjectivity of the current condition assessment method is due to the following reasons:

1. High dependency of the current condition assessment of the bridge on the experience and knowledge of inspectors;
2. High dependency of the current methods on the definition of different condition state levels;
3. Difficulties in the interpretation of the outputs of the equipment used in methods such as NDT and SHM;
4. Difficulties in having accessibility to the elements;
5. Making extensive judgments based on descriptive information;
6. Not appropriately considering changes in the condition of the components of the bridge on the safety and serviceability of the whole structure;
7. Not appropriately taking into account the vulnerability of different components of the bridge to different critical factors including live load, fatigue, environment effects, flood, wind, earthquake, and collision.

b) Rating equations

This research developed new equations and named them synthetic rating equations to provide an indication on the current and future conditions of the bridge. In developing these equations, the concept of weighting factors used in less costly methods that can be applied to a network of bridges, and the concept of criticality and vulnerability analysis used in costly and sophisticated methods such as those used for condition monitoring and assessment of particular bridges or performance-based methods, were adopted. The equations are insensitive to the number of components, hence, the condition of different bridges with different numbers of components can be compared. This insensitivity to the number of components is important, as many components of bridges are inaccessible, therefore, the judgment can be made based on the available information collected from the inspection of the bridge. Although having information on the condition of all components enables the judgment on the condition of the whole bridge to be more reliable, the method is still applicable to bridges for which adequate information on the condition of their all components is not available. This characteristic of the equations enhances the practicality of the method.

Synthetic rating equations take into account the correlation between factors, and provide different ratings associated with different critical factors. The equations include two main sets of parameters. The first set of parameters show the importance of critical factors and the second set of parameters show the weighting factors of the bridge components. As the calculations of weighting factors are costly, they are calculated once and used over a long period of time without change. This improves the practicality of the method.

c) *Importance of critical factors*

This research designed a method for identifying the importance of critical factors, which determines the contributions of different critical factors towards bridge deterioration. Critical factors include live load, extreme events (e.g. flood, wind, earthquake and collision), and environmental effects and fatigue. The method places different critical factors into different categories to enable the best method for quantifying their contributions. For extreme events, where their probability and severity of occurrence is important, it uses the risk analyses available in design standards. The usage of these risk analysis makes this method more reliable, as they are specifically developed for each extreme event. The availability of similar design standards and codes in other countries makes the usage of this method universal. For fatigue and many interrelated environmental factors, which gradually degrade the structure, probabilistic methods, such as the Markov Chain method, were taken into account as one of the best practical methods.

In order to calculate the overall importance of critical factors, Analytic Hierarchy Process (AHP) was used. As discussed in Chapter 2, AHP was selected because of the many advantages that this method has for identifying the importance of critical factors. The simplicity of the AHP and its capability for breaking down a complex system to subsystems and prioritizing them were some of the important reasons for choosing it for the method introduced in this research for quantifying the importance of critical factors.

d) Weighting factors

This research developed a method for identifying the weighting factors, which shows the criticality and vulnerability of the components and the bridge to different critical factors at the time of conducting structural analysis. Through this method, the effect of each critical factor on the structure can be evaluated. These weighting factors are used as constant numbers for 20 years, or until such time as the condition of the bridge exceeds some thresholds. The thresholds are determined based on the criteria, which were defined using Synthetic Rating Procedures (SRP).

To calculate the weighting factors of each component associated with different critical factors, the bridge structure was broken down to structural components, non-structural components and structural details. According to the method introduced in this section, the conditions of the bridge and its components in a network of railway bridges are evaluated at both safety and serviceability levels. To calculate the weighting factors of the structural components, whose health are very important for the structure, the most reliable methods are identified to be the structural analysis, or using SHM systems. It was identified that the Demand by Capacity (D/C) ratios of the components at both safety and serviceability states could provide the most reliable indication possible about the condition of the bridge. The D/C ratios were taken into account as the weighting factors of the structural components.

The demands are calculated in each individual structural component of the bridge after applying different critical forces such as live load, flood, wind, collision and earthquake. For live load, the demands are calculated in components of the structure after applying the maximum train loads that may be applied to the bridge. The standard loads are not taken into account, because the real performance of the structure should be evaluated. To calculate the weighting factors of other critical factors the load specified in design standards are used. At the safety level, the Ultimate Limit State (ULS), and at the serviceability level, the Serviceability Limit State (SLS) forces are taken into account. The capacity of the components are identified based on their condition at the time of conducting the structural analysis.

The demand by capacity ratios can also be determined at both safety and serviceability levels utilizing SHM systems. At the safety level, the strains of the important points of the bridge components associated with each load e.g. live load, earthquake load, wind load, flood load and collision load can be measured. The ratio of the measured strain at the most critical point of a component of a bridge to the yielding strain will show the D/C ratio of the component. Similarly, at the serviceability level, SHM sensors can determine the demands in the bridge components by measuring the maximum deflection and/or vibration of the component. The preceding values will be divided by the deflection and/or vibration limits identified in the design standards to obtain the D/C ratios of the components of a bridge in the network.

To calculate the weighting factors of the non-structural components, such as kerbs, and structural details such as joints, the consequences of their failure at both safety and serviceability of the structure should be evaluated. Due to the lack of investigation in the areas mentioned above, the weighting factors used in current Bridge Management Systems (BMS) can be used after scaling them down to a number between 0 to 1 to match with other weighting factors associated with structural components that will be calculated based on D/C ratios.

e) Ratings of components and bridges in the network and criteria for identifying the deadlines for actions

This research introduced criteria for identifying the ratings of each component and bridge associated with each critical factor in a network of railway bridges. The criteria also identified the deadlines for inspection, repair and maintenance, and performing structural analysis on railway bridges in the network. Engineers and managers can make decisions on the condition of the components and the bridge at different stages, based on the availability of resources.

The criticalities and ratings of the components are calculated based on their condition at the time of inspection and the weighing factors associated with live loads, as explained previously. The current condition and rating of the bridge is calculated using synthetic rating equations.

The vulnerabilities of the components to extreme events are evaluated based on the current condition of the components determined through inspection and the weighting factors associated with each extreme event. The vulnerability of the components to environment and fatigue is calculated based on the live load weighting factors and the future condition of the bridge obtained from probabilistic methods. The future condition of the bridge and the overall rating of the bridge are then calculated using the synthetic rating equations. The ratings related to each individual component and the bridge and associated with each critical factor show the criticality of their condition compared to other components and bridges in the network.

After calculating the ratings based on the criticality and vulnerability of the components and bridge associated with each critical factor, and defining the criteria for taking action, the deadlines for inspection, repair, maintenance and structural analysis are determined based on SRP.

f) Dynamic effect of train load on weighting factors of the components

This research investigated the effects of increasing the loads and speeds of the train on the structure of the bridge to evaluate the susceptibility of the components of the bridge to the above changes in load, and evaluated the criticality of the components at the time of conducting structural analysis (weighting factors of components). As the criticality of the components in carrying live load was very important, more detailed investigations on calculating the weighting factors of the components (D/C ratios of the components) were conducted in Chapter 4. This study was conducted on a simply supported bridge, the most common type of railway bridge in Australia. It was shown that this typical bridge could represent the structural behaviour of simply supported bridges in a network of railway bridges in Australia. In the scope of this study, the details of the track structure, such as track and ballast, were not taken into account, as their effects on the dynamic responses of the bridge were identified as insignificant according to the literature, and due to feasibility reasons.

According to the results, conducting dynamic structural analysis was determined to be necessary, as the effect of resonant vibration was found to be significant on the D/C ratios of the components. The configuration of the axles, the speed of the train and the length of the span were identified as important factors in resonant vibration. In this study, it was identified that applying speed restrictions on bridges in poor condition might not always decrease the D/C ratios of the component. In other words, applying restrictions on speed could sometimes make a bridge unsafe for carrying the train load.

g) Application of the method on a network of railway bridges

In order to illustrate the application of the method, it was applied on a network of two bridges to show the practicality of the method and discuss the outcomes. Live load, wind, earthquake, collision, and flood forces were applied to the structure to calculate the criticality and vulnerability of the components and bridges. The current and future conditions of the bridges were also evaluated using synthetic rating equations and based on the Synthetic Rating Method. Finally, the ratings of components and bridges associated with each critical factor were identified. Contrary to current rating methods, which provide one rating for each component and bridge, the Synthetic Rating Method identifies different ratings for each component and bridge, which show their vulnerability to different critical factors.

The Synthetic Rating Method is a far more reliable method compared to current practical methods, because it uses AHP to improve the decision making process, utilizes risk assessment procedures in current design standards to improve the predictions of the future life of the bridge and its components, and takes into account different levels for different critical factors to apply the most reliable method possible. In addition, the structural configuration is taken into account and the criticality and vulnerability of each component due to each single factor is identified by utilizing reliable tools, including structural analysis and SHM systems.

The Synthetic Rating Method is practical enough to be applied to a network of thousands of railway bridges, as the contribution of the critical factors can be identified through a simple process and by answering a few simple questions. Structural analysis for identifying the criticality and vulnerability of the components is simple and conducted as infrequently as possible. SRP can communicate with managers and engineers by providing them with descriptive information and meaningful engineering figures. Synthetic rating equations are not sensitive to the number of components.

One of the key advantages of the method introduced in this research is that this method has great potential for improvement by conducting more investigations on consequences of failure and providing more comprehensive and reliable data about the condition of the bridge in the future. Although due to the complexity of the problem, the subjectivity of the condition assessment and rating thousands of bridges at a network level cannot be totally removed, the method introduced in this research significantly reduces this subjectivity, and as a result, the restricted resources for maintaining railway bridges safely and serviceability, can be much more efficiently used.

6.2 LIMITATIONS, OPENING ISSUES, AND FUTURE WORK

This research developed a system for assessing the current and future conditions of a network of railway bridges and rating them accordingly. This method can be applied to road bridges as well. The method is based on the importance of critical factors and the criticality and vulnerability of the components and bridges in the network. As mentioned previously, the method has great potential for improvement, and can be used as a platform that can incorporate the results of investigations in the following areas to improve its outcomes over time.

1) *Developing a method of recording the cause of damages and the cost of repair related to each component of the bridge.*

This will help to improve the reliability of the figures mentioned in Table 3-1 over time. Therefore, the contribution of each critical factor will be more reliably calculated for the network of the bridge.

2) *Conducting more investigations on the consequences of failure of any non-structural components or structural details on the safety and serviceability of the bridge subjected to different critical factors such as fatigue.*

The results can be used in the form of new weighting factors associated with the new critical factors, or can be used to enhance the accuracy of the current weighting factors related to non-structural components and structural details. These weighing factors can then be incorporated into the rating equations introduced in this research to continuously improve the reliability of the method in future.

3) *Developing more effective methods to access and evaluate the condition of different components of the bridge.*

As examples of the above methods, utilizing new technologies such as flying robots which can carry cameras and tools for NDT tests, or constructing additional members in the structure of the bridge to facilitate accessing the components of the bridge, can be quoted. Collecting adequate data about the condition of more components of the bridge improves the results of the SRP. Development in NDT tools in increasing their reliability and making them less costly and more available, and substituting them with visual inspection will improve the results of inspection and enhance the reliability of the levels introduced in Table 3-10 and Table 3-21.

In addition, the documents provided by engineers can be used as samples of the different levels of the conditions for each type of component (e.g. Table 3-10 and Table

3-21). This will help to improve the consistency of the results of inspections conducted by different inspectors and improve the reliability of the data provided by them.

4) *Utilizing SHM systems as much as possible in the synthetic rating procedures to calculate the criticality and vulnerability of the components.*

This enables engineers to continuously monitor the performance of the bridge and hence, more frequently update the criticality and vulnerability of the components introduced in this research. By utilizing the SHM method on an important bridge, on some occasions, instead of calculating the demand by capacity ratios of the components of bridges by conducting structural analyses, they can be determined at both safety and serviceability levels by measuring them using sensors. At the safely level, strain gauges can be used at critical points of critical components and they can be compared against yielding strain. The structural analysis will be used to identify the critical locations in bridges and their components, and the sensors can be placed there to monitor the criticality and vulnerability of the condition of each bridge in the network.

At the serviceability level, the deflections and vibrations of components can be measured by sensors and used as demands. The capacity at the serviceability limit will be the limits determined by standards. As a result of using the SHM system for calculating the demand by capacity ratios of the components, the ratings of the components and the bridge in the network of bridges can be constantly updated. In addition, the reliability can be improved, because the demand by capacity ratios and criticality and vulnerability of the components of a bridge will be calculated through direct measurement.

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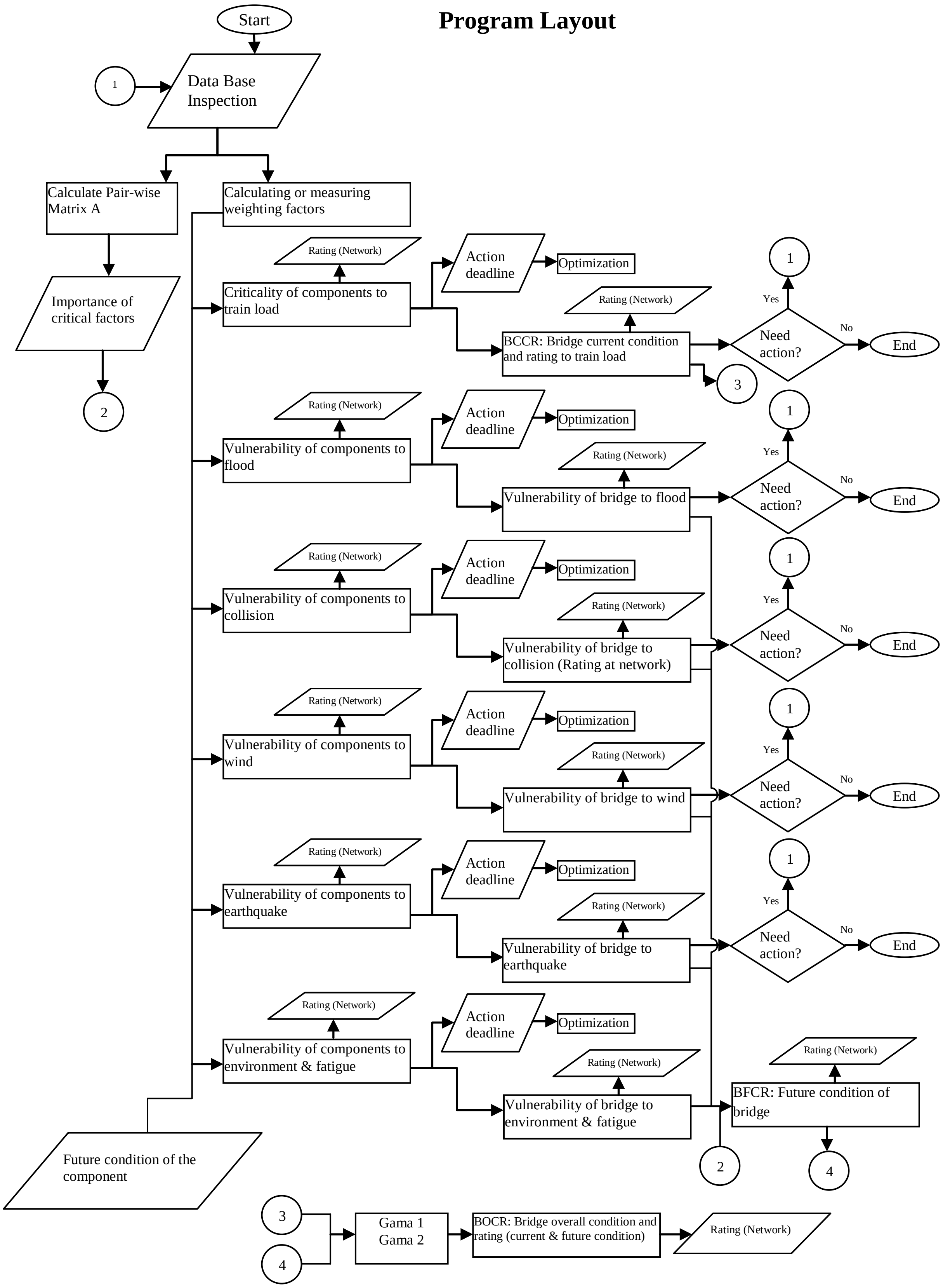
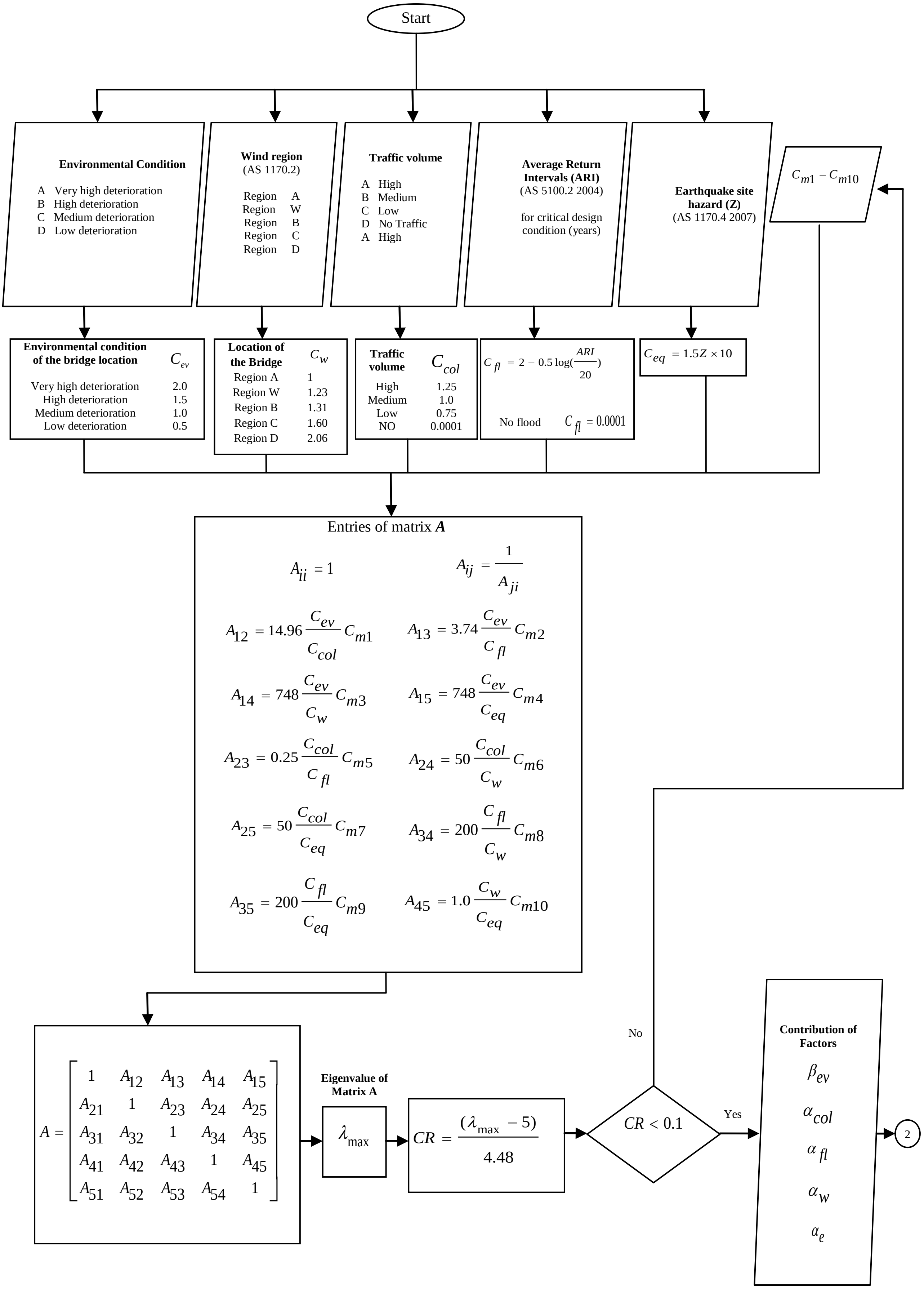
Appendices

Appendix A: Algorithm of Synthetic Rating Method

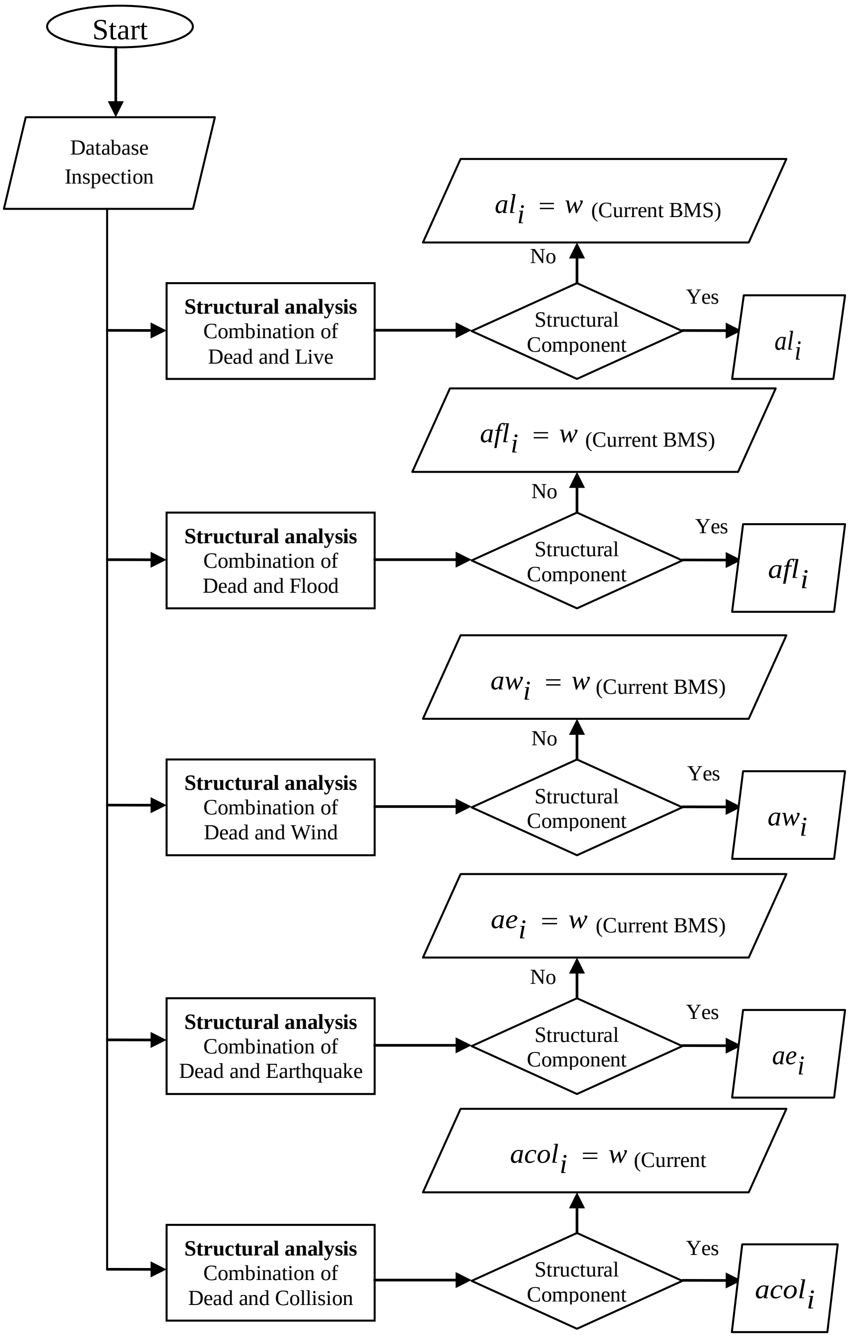
Program Layout



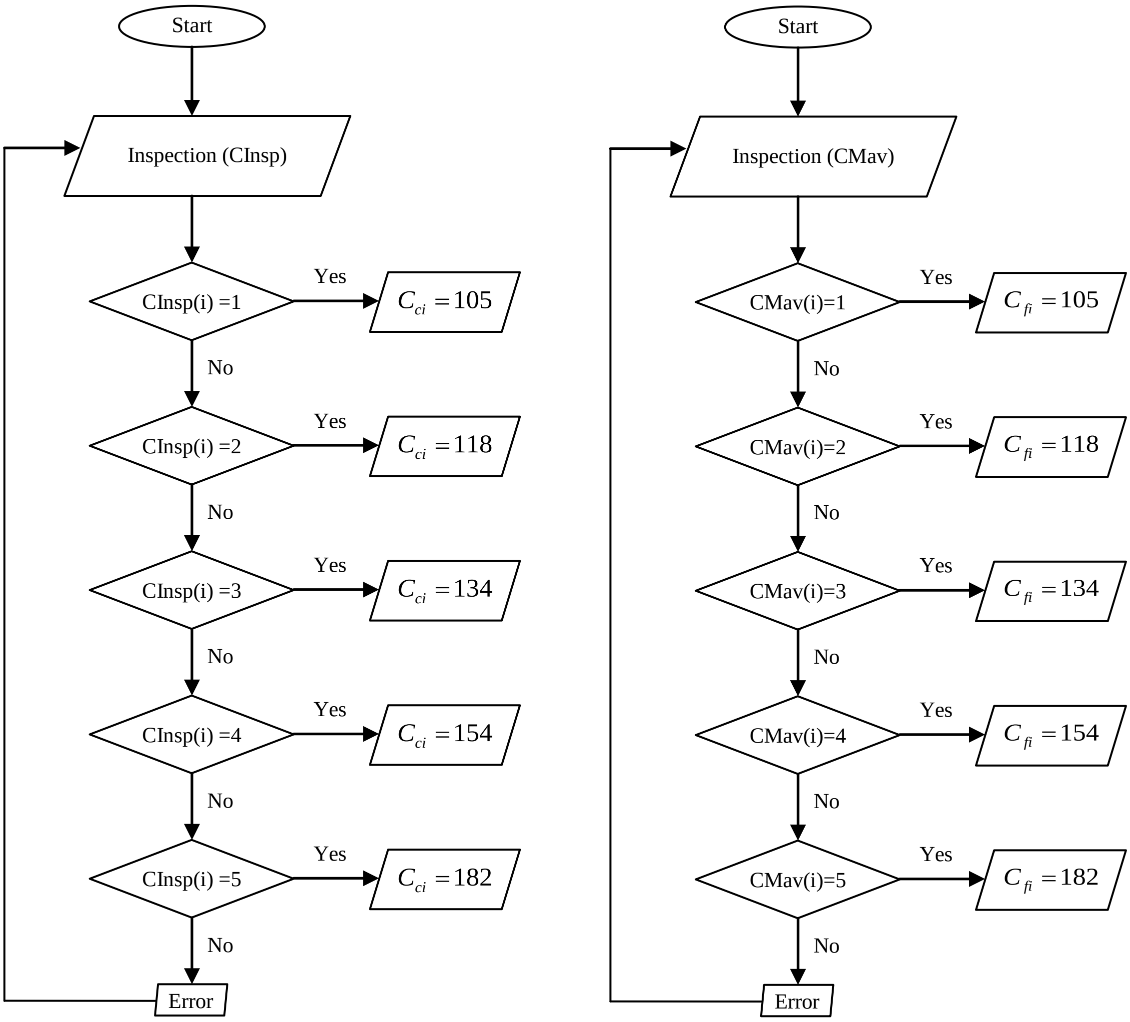
Calculations of the importance of critical factors



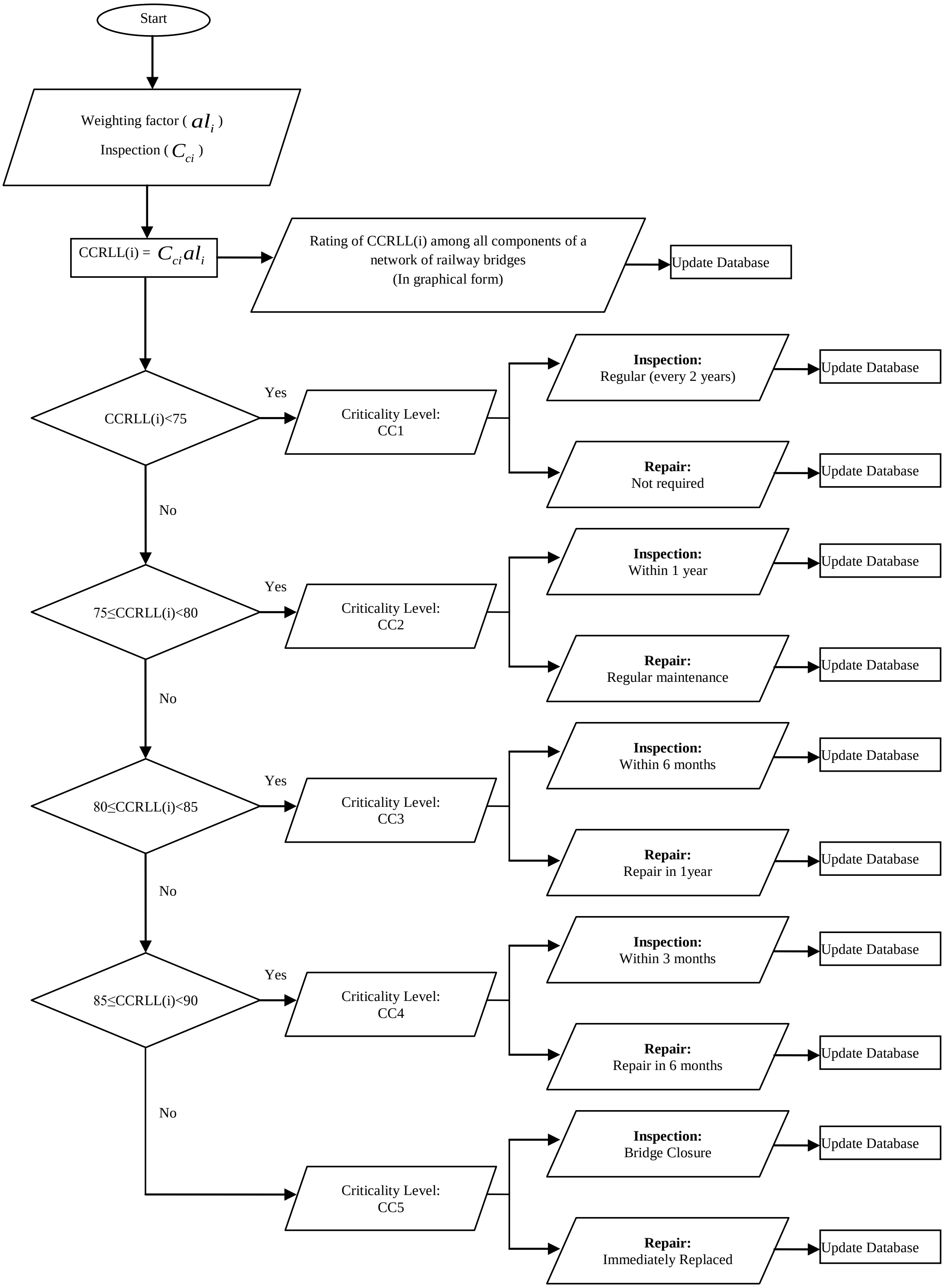
Calculating weighting factors



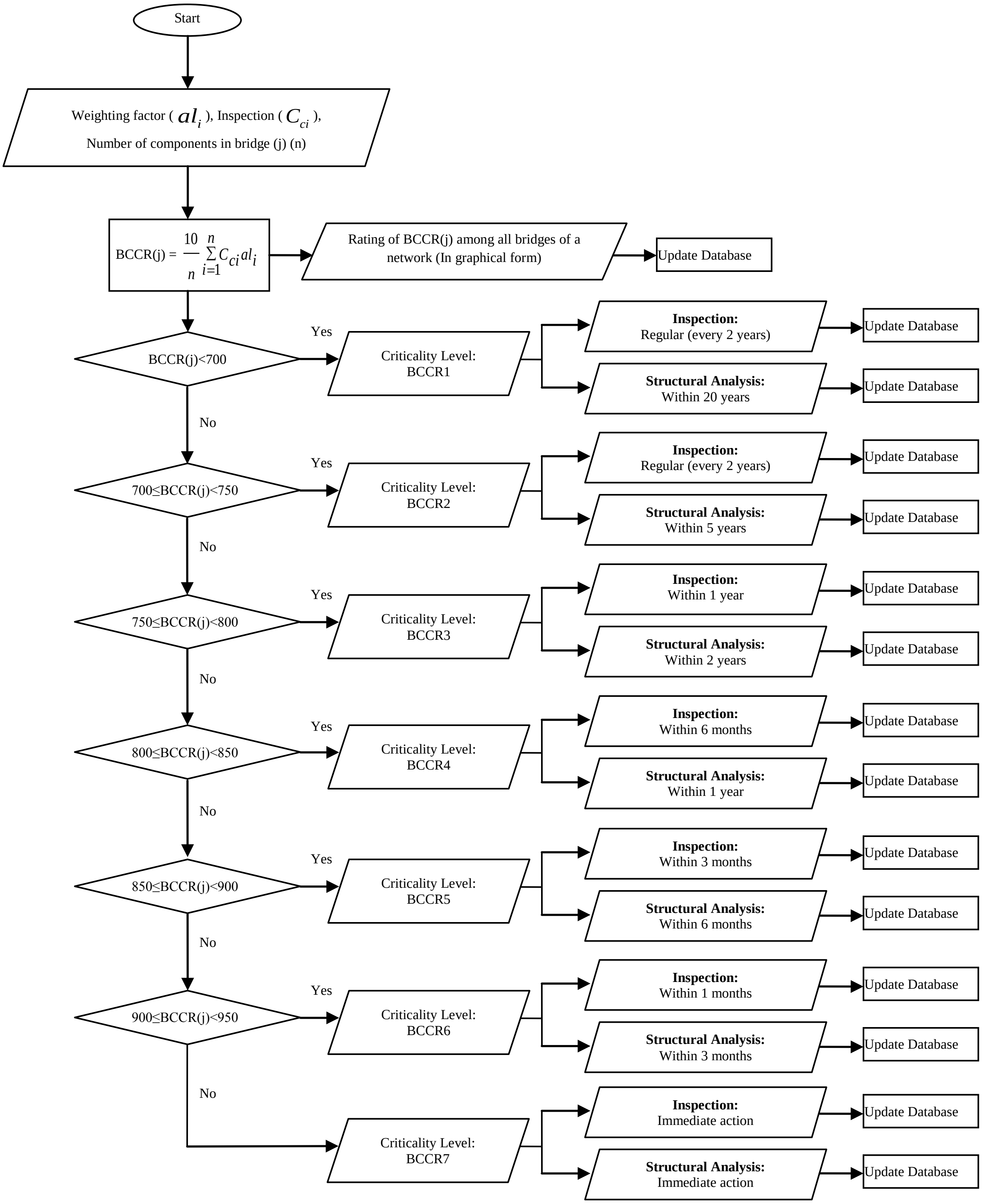
Calculating C_{ci} and C_{fi}



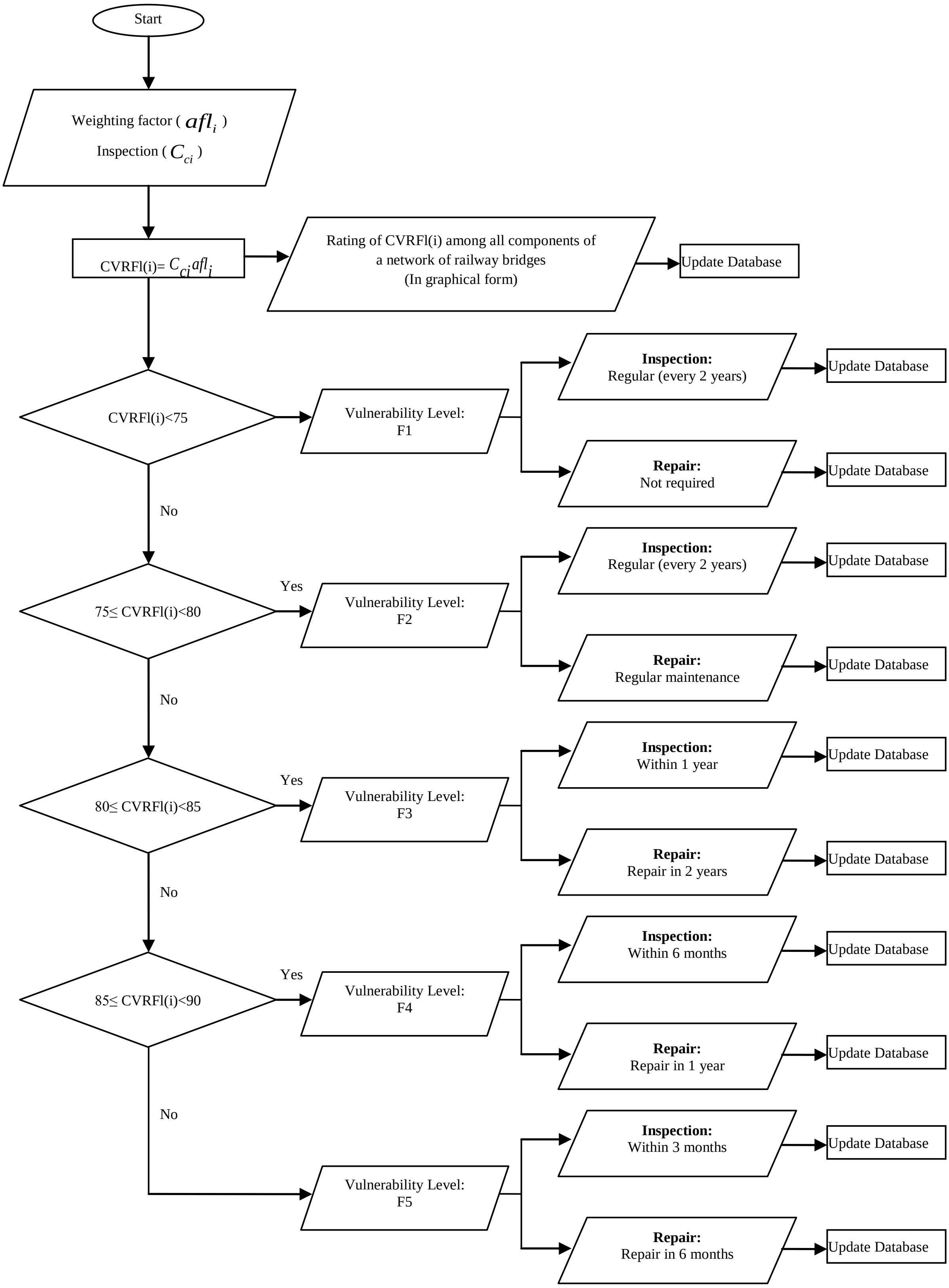
Criticality and rating of the component (i) to train load (live load)



Current condition and rating of the bridge (j) in network of railway bridges

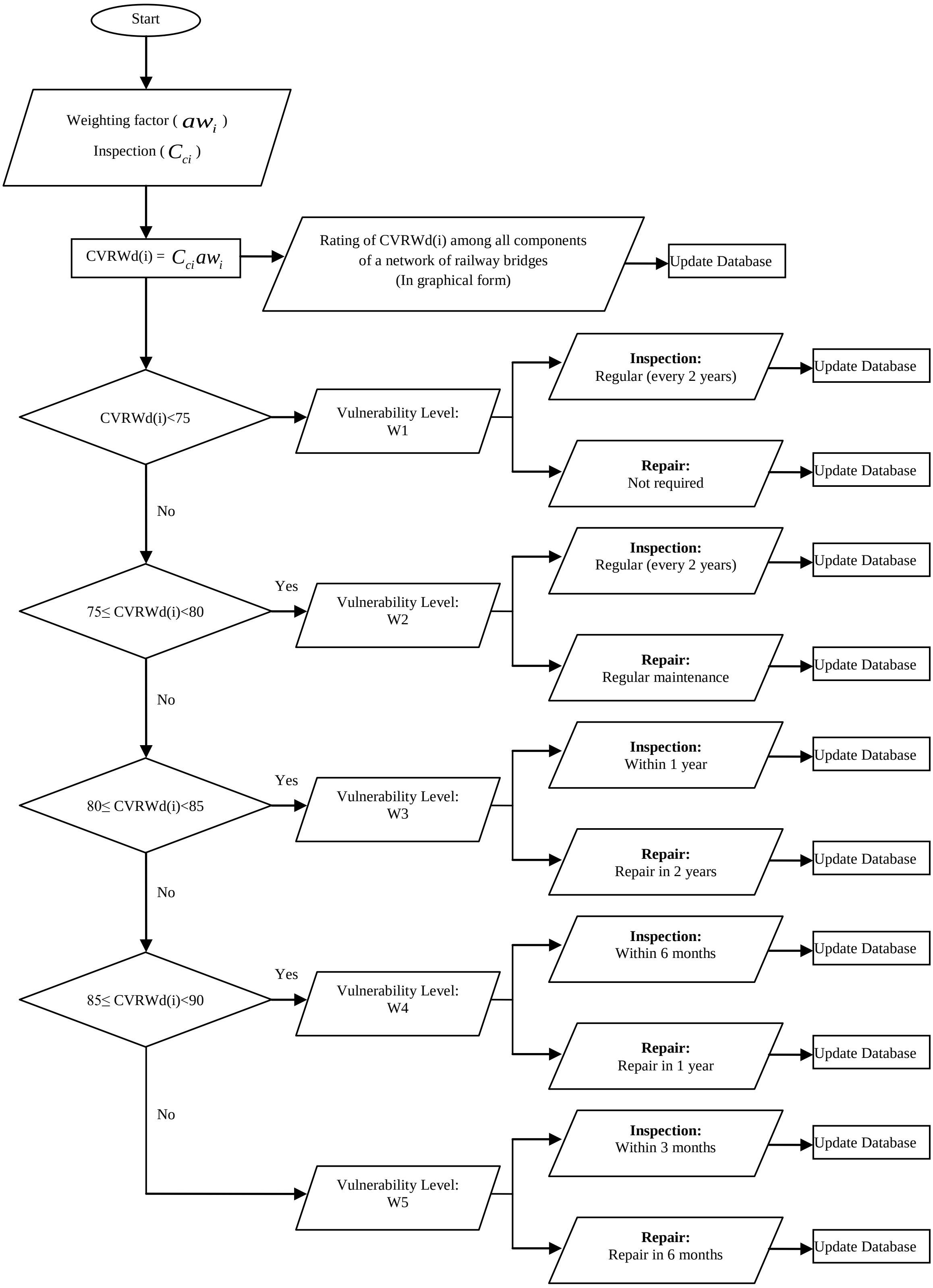


Vulnerability and rating of the component (i) to flood



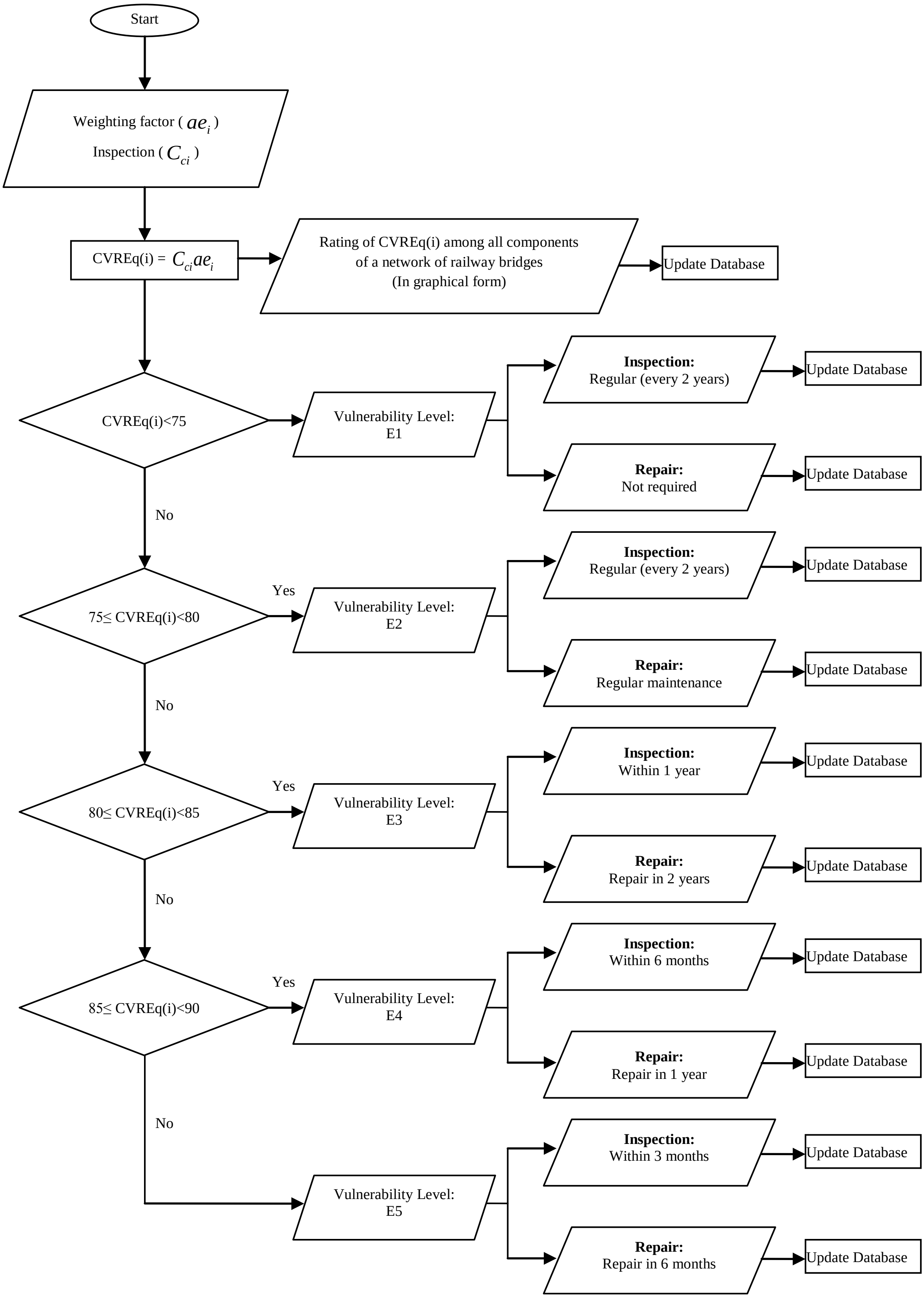
Vulnerability and rating of the bridge (j) to flood

Vulnerability and rating of the component (i) to wind



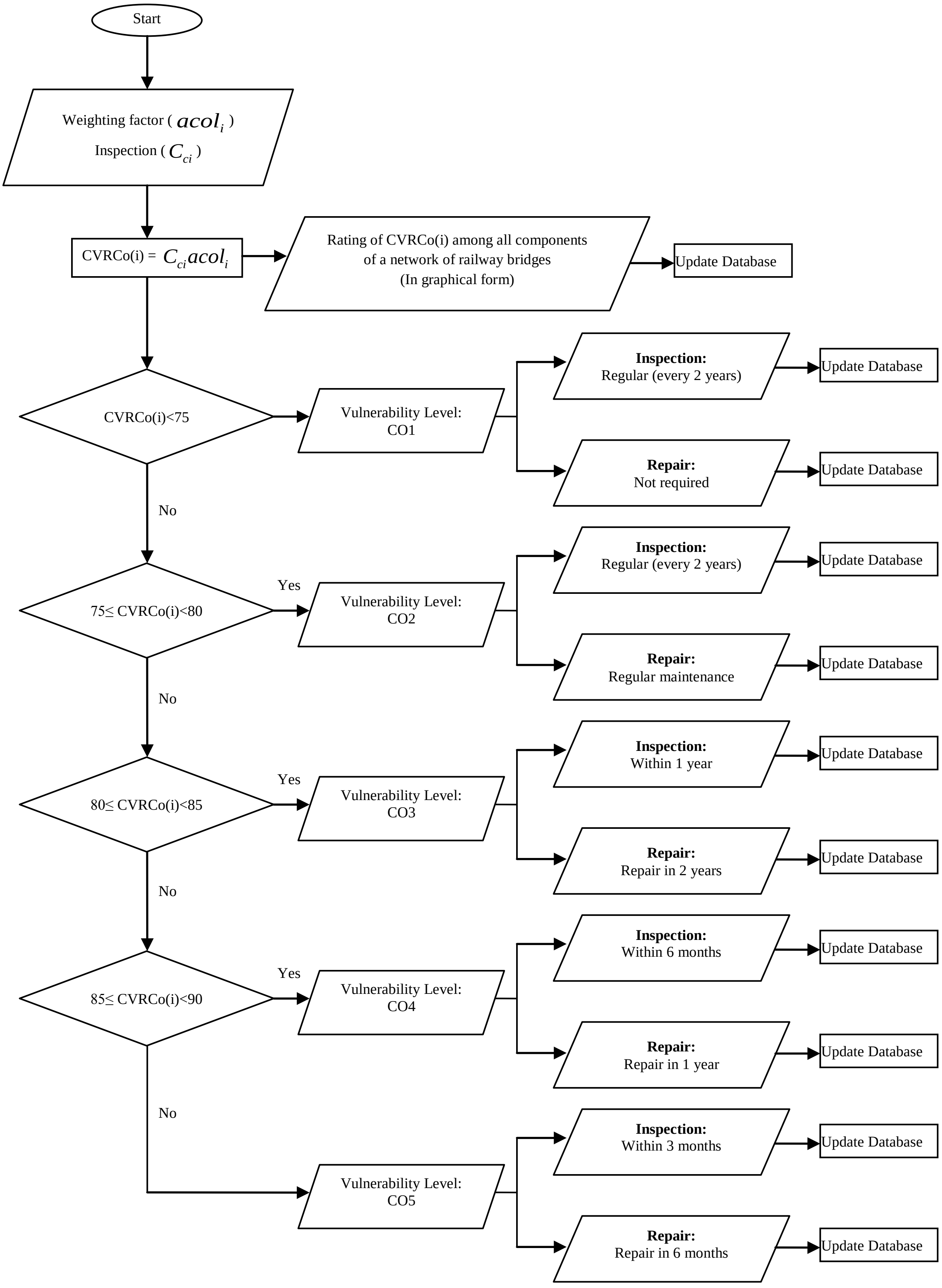
Vulnerability and rating of the bridge (j) to wind

Vulnerability and rating of the component (i) to earthquake

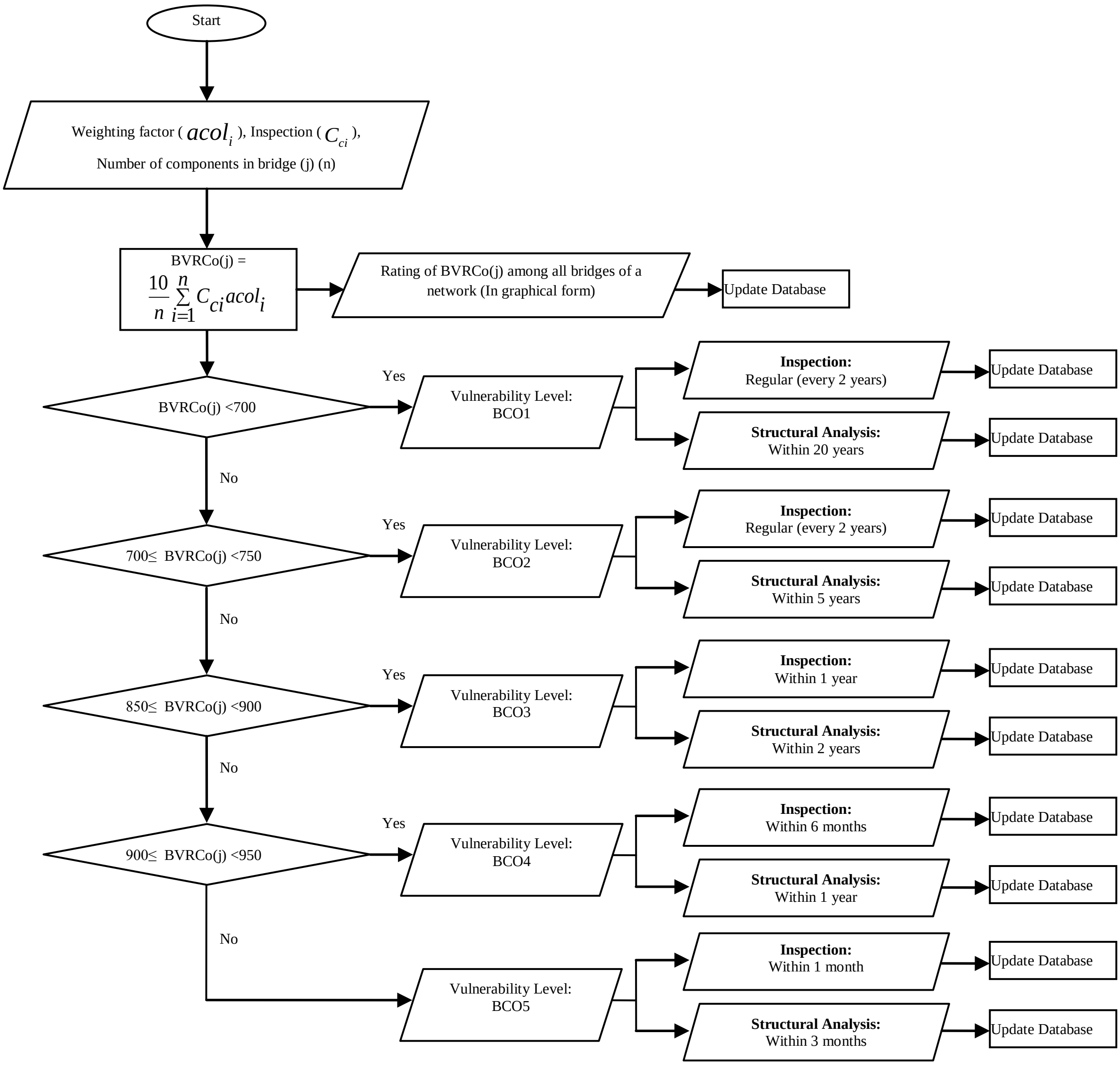


Vulnerability and rating of the bridge (j) to earthquake

Vulnerability and rating of the component (i) to collision

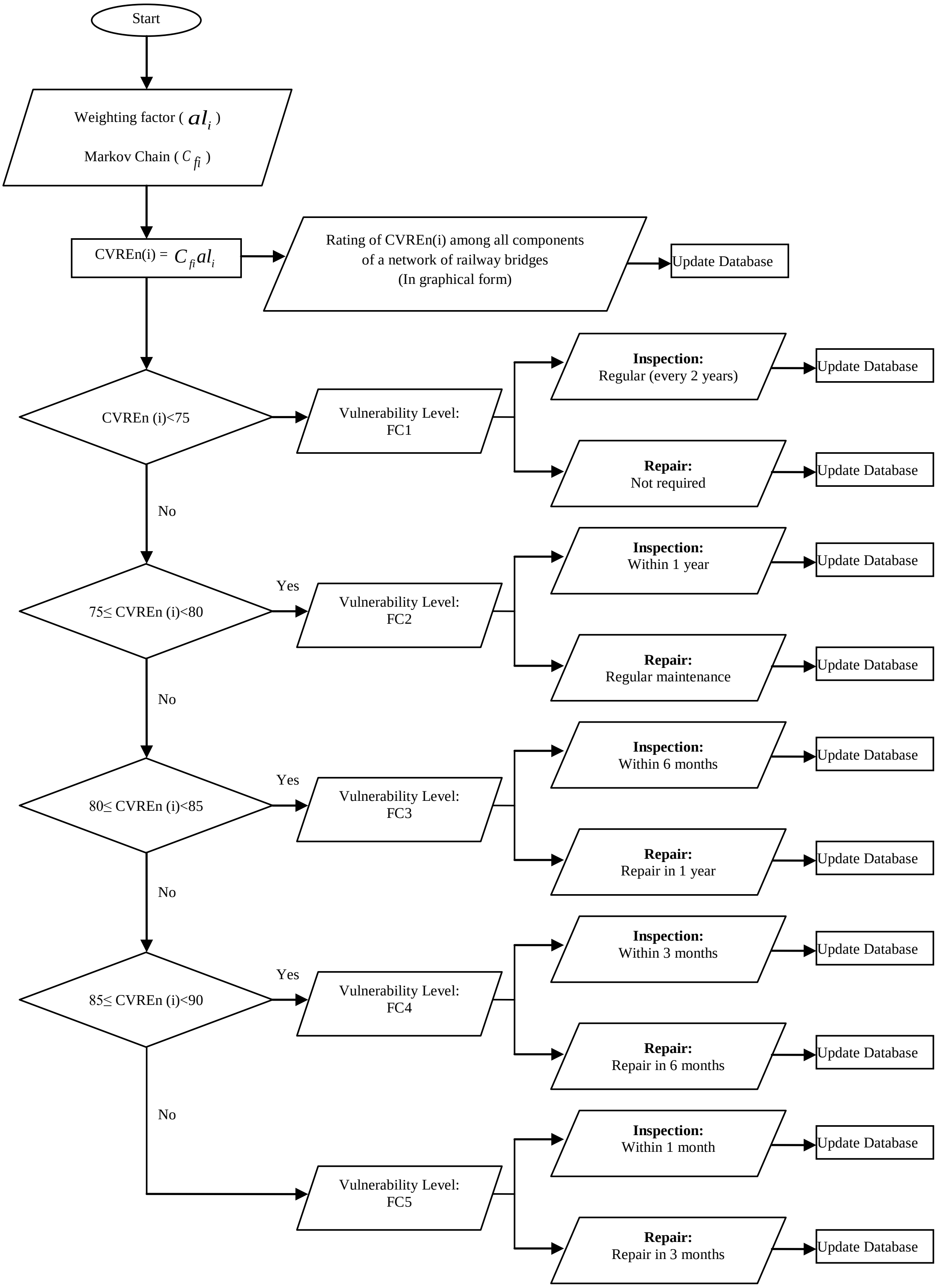


Vulnerability and rating of the bridge (j) to collision

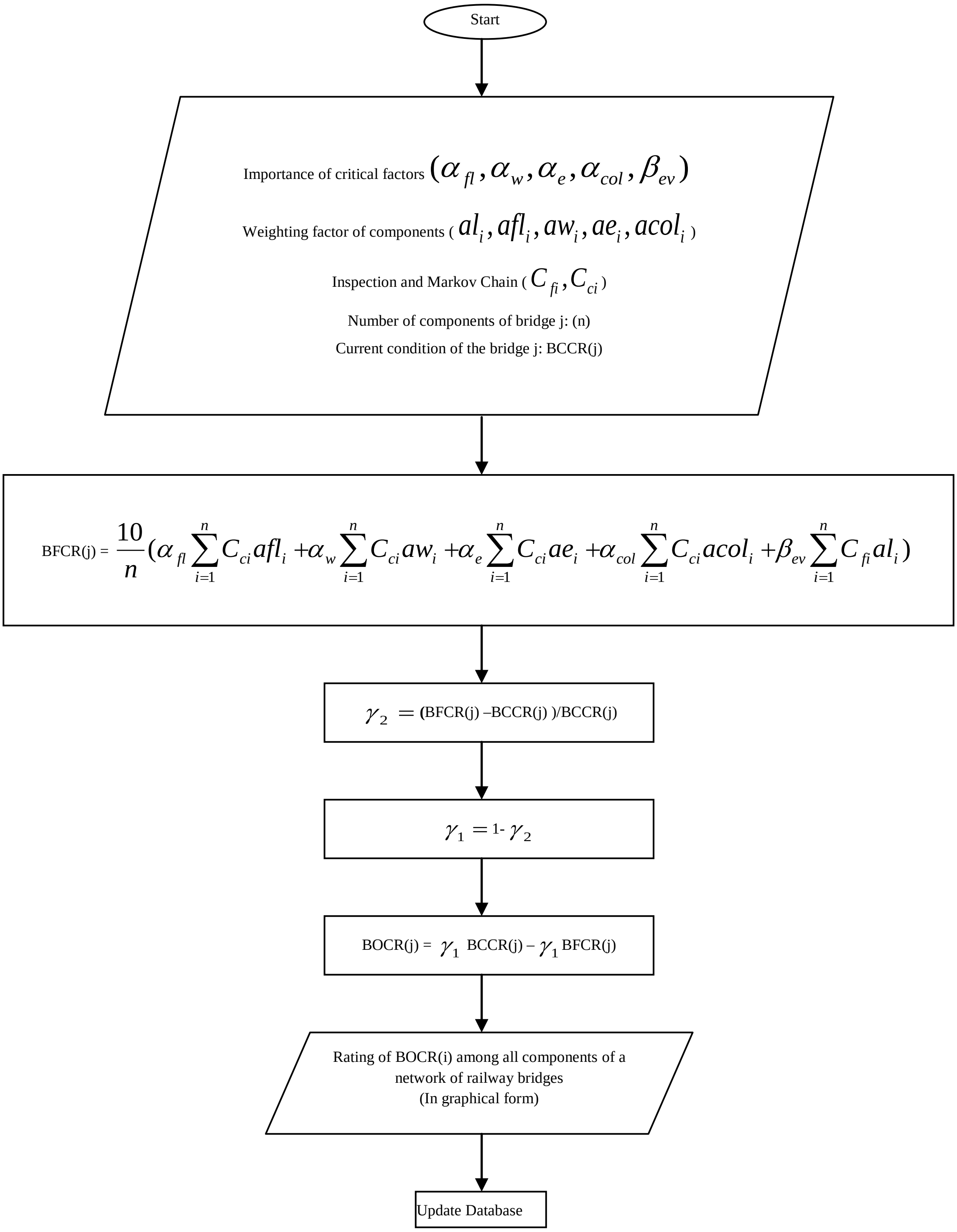


Vulnerability and rating of the component (i) to environmental and fatigue

(After the prediction time)



Rating of the bridge at network level based on its current and future condition



Appendix B: Publications Derived from this Research

JOURNAL ARTICLES (Published)

Aflatooni, M., Chan, T. H. T., Thambiratnam, D. P. (2015). A New Look at the Restrictions on the Speed and Magnitude of Train Loads for Bridge Management, *the International Journal of Structural Engineering and Mechanics, 53*(1) 89-104. doi: http://dx.doi.org/10.12989/sem.2015.53.1.089

Aflatooni, M., Chan, T. H. T., Thambiratnam, D. P. (2014). Synthetic rating procedures for rating railway bridges. *Journal of Bridge Engineering.* doi: 10.1061/(ASCE)BE.1943-5592.0000623

Aflatooni, M., Chan, T. H. T., Thambiratnam, D. P., & Thilakarathna, I. (2013). Synthetic rating system for railway bridge management. *Journal of Civil Structural Health Monitoring, 3*(2), 81-91. doi: 10.1007/s13349-013-0035-6

CONFERENCE PAPERS

Aflatooni, M., Chan, T. H. T., Thambiratnam, D. P., & Thilakarathna, I. (2012). *Classification of Railway Bridges Based on Criticality and Vulnerability Factors.* Paper presented at the ASEC Australian Structural Engineering Conference, Perth.

Aflatooni, M., Chan, T. H. T., Thambiratnam, D. P., & Thilakarathna, I. (2012). *Synthetic Rating System for Railway Bridge Management.* Paper presented at the First International Conference on Performance Based and Life-Cycle Structural Engineering (PLSE), Tsimshatsui, Hong Kong, China.

Aflatooni, M., Chan, T. H. T., & Thambiratnam, D. P. (2013). *Susceptibility of the Critical Structural Components of Railway Bridges to the Changes in Train Speed.* Paper presented at the APVC 2013, 15th Asia Pacific Vibration Conference, Jeju, Korea.

Aflatooni, M., Chan, T. H. T., & Thambiratnam, D. P. (2013, September 2013). *A New Method for Quantifying the Contribution of Different Critical Agents on Railway Bridge Deterioration.* Paper presented at the Proceedings of the Fourteenth International Conference on Civil, Structural and Environmental Engineering Computing, Cagliari, Sardinia, Italy

Aflatooni, M., Chan, T. H. T., & Thambiratnam, D. P. (2013). *A Novel Method for Quantifying the Criticality and Vulnerability of the Components of Railway Bridges*. Paper presented at the 10th World Congress on Railway Research 2013, Sydney, Australia.

CONTRIBUTION TO FOLLOWING REPORTS

Software Plan of the development (2014), Life Cycle Management of Bridges Project, CRC for Rail Innovation, Brisbane, Australia

Final Report (2013), Life cycle management of railway bridges, CRC for Rail Innovation, Brisbane, QLD, Australia

Bridge classification (2012), Life cycle management of railway bridges, CRC for Rail Innovation, Brisbane, Australia

Factor Identification for Asset Management (2011), Life Cycle Management of Bridges Project, CRC for Rail Innovation Brisbane, Australia