# Classification of Railway Bridges Based on Criticality and Vulnerability Factors

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## ABSTRACT

Bridges are currently rated individually for maintenance and repair action according to the structural conditions of their elements. Dealing with thousands of bridges and the many factors that cause deterioration, makes this rating process extremely complicated. The current simplified but practical methods are not accurate enough. On the other hand, the sophisticated, more accurate methods are only used for a single or particular bridge type. It is therefore necessary to develop a practical and accurate rating system for a network of bridges. The first most important step in achieving this aim is to classify bridges based on the differences in nature and the unique characteristics of the critical factors and the relationship between them, for a network of bridges. Critical factors and vulnerable elements will be identified and placed in different categories. This classification method will be used to develop a new practical rating method for a network of railway bridges based on criticality and vulnerability analysis. This rating system will be more accurate and economical as well as improve the safety and serviceability of railway bridges.

## KEYWORDS

Bridge Classification; Criticality; Vulnerability; Bridge Management; Rating Bridges

## INTRODUCTION

Structural conditions of bridges change with time due to environmental effects, changes in quality and magnitude of loads, etc. (Shih et al., 2009). Prioritising bridges according to their structural conditions for maintenance, repair or replacement action is one of the most important parts in every Bridge Management System (BMS). Collecting or identifying many factors, such as adequate information on the severity and extent of damage, environmental condition, geometry of the structure, material, loading, are necessary, to evaluate the condition of railway bridges with acceptable accuracy. More factors increase the complexities of the structural models and consequently decrease the practicality of the rating system. Sasmal and Ramanjaneyulu (2008) consider that, to ensure the existing bridges are still able to carry loads, developing a rational algorithm for evaluating their condition is an immediate need. In fact, an economical plan for providing adequate safety and functionality for bridges is highly dependent on the accuracy of current condition assessment and future condition prediction of bridges. The efficiency of this condition assessment and rating system for a group of bridges is therefore dependent on how critical factors and the correlation between them are identified and classified.

The condition of each structural element in current practical inspection manuals is assessed during an inspection process. Then the condition of a bridge is derived from the condition of each individual element (Austroads, 2004). After the components and elements of the bridge have been classified, based on the importance of each element for the integrity of the structure a weighting factor is assigned to them (Ryall, 2010), and the condition of the whole structure will be evaluated accordingly. These practical rating systems for rating a network of railway bridges, such as New York method (Ryall, 2010), are too simplistic and shall be improved to achieve more accuracy in condition assessment of bridges. Because for determining these weighting factors they do not take into account factors such as the geometry of different structures or the importance of structural elements when the bridge is subjected to different environmental conditions or types of loading.

Attempts were made in current inspection manuals such as Condition Assessment of Short-line Railroad Bridges in Pennsylvania (Laman and Guyer, 2010), to incorporated the contribution of other critical factors, such as scour and fatigue, in evaluating the risk of failure. Determining the criticality of elements subjected to particular crucial factors was also tried. For instance AASHTO (2011) shows that spread footings are more critical than piles where they are subjected to scour and erosion. Although the efficiency of these rating methods by considering critical factors increased, the response of bridges with different geometry, and material, to these factors through an appropriate classification for a network of bridges has not still been taken into account.

Scholars have made a significant attempt to incorporate more critical factors, and devise a more accurate method for condition assessment and rating bridges. Wong (2006) adopted a criticality and vulnerability analysis and Analytic Hierarchy Process (AHP) system to more accurately evaluate the structural condition of the Tsing Ma Bridge in Hong Kong. Xu et al. (2009) conducted criticality and vulnerability analyses and used Fuzzy logic with AHP to developed a rating system for the Tsing Ma Bridge to deal with uncertainties from inspection process. Through criticality and vulnerability analysis, by performing structural analyses critical factors such as the alternative load paths, maximum design stress, and remaining life, as well as vulnerability factors including corrosion, damage, and wear are identified, and the condition of the bridge is assessed. AHP builds a hierarchy structure to solve a complex problem and in a bridge rating system it is used for the classification and prioritization of factors such as environmental impacts, and fatigue. Saaty (1980) developed AHP method (Sasmal and Ramanjaneyulu, 2008), and Zahedi (1986) conducted a comprehensive investigation on the methodology of AHP and its applications. Tee (1988) explained the mathematical concept and definition about the Fuzzy Logic operations in detail.

The results of these methods were reliable because the effect of different factors on the structure were calculated more accurately by identifying and classifying the criticality and vulnerability factors and conducting analyses associated with them. However, they were all designed for one bridge only, and therefore not applicable for a network of bridges. Furthermore, their methods need a large amount of accurate data about the bridge, complicating the analytical process and making these rating systems impractical for a network of thousands of bridges. Bridges should first be classified if a network of bridges is to be compared and rated and the rating method should be simplified for different classifications.

AHP was used by other scholars for classifying and categorizing factors on different levels. Sasmal and Ramanjaneyulu (2008) developed a multicriteria process for condition evaluation of reinforced concrete bridges, and Zayed et al. (2007) applied AHP and utility function for risk assessment of bridges with unknown foundations. Tarighat et al. (2009) used Fuzzy

Logic for rating bridges with a concrete deck. These researchers all proved that rating one type of bridge, such as reinforced concrete bridges, or a part of a bridge such as a foundation or concrete deck, based on identified and classified criticality factors is practical. However, their classification has not yet been designed for a network of bridges with different geometry, material, loading, and environmental conditions.

An appropriate classification of bridges means crucial factors will be taken into account efficiently and consequently the railway bridge rating system at a network level will be more practical, economical and accurate. Using resources including time, expertise and equipment efficiently for improving the safety and serviceability of railway bridges will be dependent on a rating system, founded on an appropriate classification.

## CLASSIFICATION METHOD FOR A NETWORK OF RAILWAY BRIDGES

The important factors in classifying railway bridges include, age, geometry of the structure, material, loading, and environmental effects. To this purpose, data for a group of about 1100 railway bridges in Australia were collected from inventory data and inspection reports. Preliminary statistical analyses were then conducted to identify the most important factors that affect the current and future condition of these railway bridges.

### Survey and Results

As can be observed in Figure 1 more than 70% of these railway bridges are older than 40 years. This means taking action for their maintenance or repair may be required, and providing accurate inspection reports about their condition is essential. These reports should provide sufficient and precise information about the critical elements of these railway bridges, according to their classification.

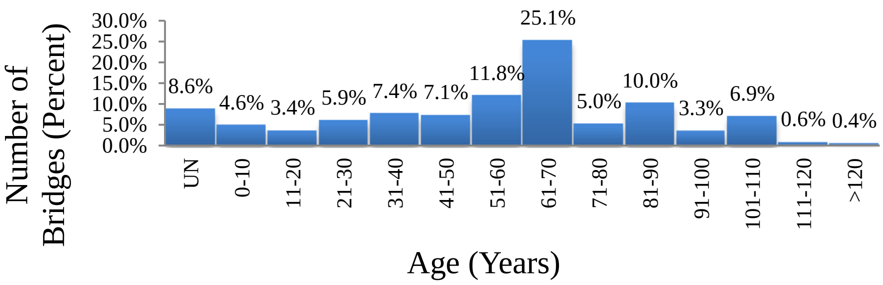


Figure 1 Age of railway bridges in a sample of 1122 in Australia

Steel was observed as the main material used in superstructure components of railway bridges. Therefore, the effect of corrosion will be one of the most critical factors for the durability of the bridge. Fatigue impact was also identified as a crucial factor for deteriorating railway bridges with steel structures. Timber is no longer used as a structural material. However, as many existing timber bridges are still in service for many years, and the decaying timber components are replaced by steel or other viable alternative materials, stucutral analyses on these bridges are requried, to predict their remaining service life as well as load capacity. Furthermore, the analysis of this collected data illustrates the wide use of reinforced concrete in the recent past. Therefore, evaluating the current condition of railway bridges constructed with reinforced concrete seems to be a rational strategy. Mass concrete and masonry have been widely used as substructure materials and their condition and vulnerability should be assessed in the inspection process. However, a structural analysis, considering the ambiguity in their structural behaviour (Orbán and Gutermann, 2009) may not be valuable.

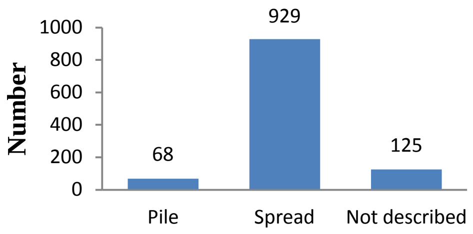


Figure 2 Foundation Type

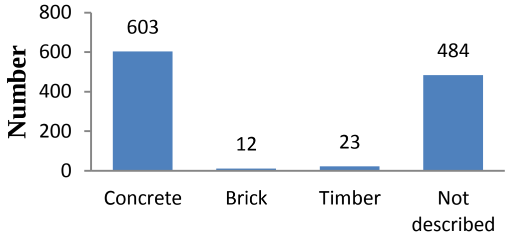


Figure 3 Foundation Material

The statistical analyses of this data also shows that the inspection process should focus on spread footings as they are used much more frequently than piles (Figure 2). However, pile is one of the common foundation type for new railway bridges, and its behaviour is required to be evaluated through a structural analysis. In addition, the materials of about 45% of the foundations of railway bridges were not identified through the inspection process (see Figure 3) which means accessibility to these structural elements is very limited and the type of questions that is required to be answered by inspectors should be designed considering these restrictions. Furthermore it was identified that, the changes in temperature, and scour, are two other important factors for deteriorating railway bridges and decreasing their remaining service life in Australia. Changes in temperature induces internal stresses and changes the characteristics of the critical structural components of bridges (Catbas et al., 2008). Based on identified factors the following classification method for a network of bridges will be developed.

**Classification Method**

To improve the accuracy of practical methods used for rating a network of bridges, researchers have attempted to identify crucial factors and critical elements of structures through conducting criticality and vulnerability analyses and classifying them in order to develop a more reliable condition assessment method for bridges. However, these attempts based on detailed structural analysis were primarily focused on a single bridge or identical elements of bridges or one type of bridges at a time and hence, the structural condition of a network of bridges have not yet been assessed. Developing technologies, data analyses and engineering knowledge facilitate criticality and vulnerability analysis. However, they are still too complex to be applied to a network of thousands of bridges. That is, each individual bridge requires extensive information, rigorous structural analyses, profound engineering knowledge, and almost unlimited time. Therefore these criticality and vulnerability analyses should be modified and simplified for rating a network of bridges. To this purpose railway bridges at a network level should be classified first.

It is not practical and economical to conduct a detailed inspection and structural analysis on every individual railway bridge. Therefore, this classification will divide the network of bridges into several groups. A typical analytical model that can represent a group of railway bridges based on the similarities between the geometries of their structures will be created. For instance, after conducting some preliminary statistical analysis on approximately 1100 bridges, 7 typical bridges have been identified as representatives of the entire network which include simply supported, continuous Supported, rigid frame, truss, and different types of

Arch bridges. Factors such as loadings, and environmental effects that impact on the current and future condition of that typical bridge will then be classified based on their unique characteristics. To take into account the correlation between these factors, it is essential to classify bridges appropriately. Ultimately this classification will be used for criticality and vulnerability analyses for determining weighting factors related to different critical factors for each structural element. The results will then be used to develop a new rating system reported later in another paper. Evaluating the structural condition of typical bridges by considering different critical factors will increase the accuracy of the condition assessment and rating system that uses this classification method. Furthermore, performing structural analyses on typical bridges, instead of each individual bridge in a network of thousands of bridges will improve the practicality of the method. Different components of this classification, including the structure geometry, element materials, loading types and characteristics, environmental conditions are explained as follows.

*Structure Geometry.* The behaviour and response of a structure according to its geometry will be changed. To incorporate the geometry of railway bridges into the rating process, the structure will be divided into the two main components of superstructure, and substructure. Each component consists of several elements according to the bridge structural configuration. It is important to identify the fracture critical elements of the structure according to its geometry. Fracture critical elements/members (FCM) are those structural elements where any failure in them may cause the failure of a portion or the whole structure (Bridge Inspection Committee, 2010; Catbas, et al., 2008). Foundations are not easily accessible in the inspection process and as a result, it is difficult to evaluate their condition. Therefore, the number of questions that can be answered by an inspector will be less and consequently the classification system should be designed accordingly. Once damages been identified through the inspection process, the geometry of the model will be updated. The current condition can then be compared with the previous or, as built condition. The next step for creating the mathematical models for these typical bridges is to identify the material and assign them to the geometry.

*Element Materials.* Different types of materials including steel, concrete, timber and masonry are considered and will be assigned to the structure. For each of these materials for example for concrete, subcategories such as mass, reinforced, pre-stressed, and post-tensioned are also defined.

*Loading Types and Characteristics.* According to the differences between loads, they can be put in different categories. The load type and its position may lead to a critical condition for the structure (Boothby, 2001). Some loads are unique for each individual railway bridge, but some others can be grouped the same for a network of bridges. For instance, for each single bridge the dead and live load is different and their effects are on the current capacity of the bridges. If the live load exceeds its limit, a part or the whole structure may collapse instantly. But loads such as wind or earthquake are almost the same in an area, although the responses of the structures to them are different. The quantity of these types of lateral loadings can be calculated from the available standard's maps such as AS 1170.2 (2002), and the response of the structure based on its geometry and material can be estimated for each typical railway bridge.

Load combination factors will be used to compare the effects of each type of loadings. These load combination factors can be obtained from current standards. It improves the accuracy of this rating system by utilizing available knowledge. The effect of fatigue as one of the most important factors in deteriorating railway bridges will also be analysed and incorporated to the classification. Live loads applied to railway bridges may change significantly over time (Nielsen et al., 2011). Therefore, live load and its dynamic effect used for load rating of bridges and estimating the live load capacity of the structure, will be the most important element of this classification. Structural health monitoring (SHM) can be used later to evaluate the effect of live load on the damaged structure with high level of confidence for validation of criticality analyses (Catbas et al., 2007). Recent development in SHM in Australia is summarized by Chan and Thambiratnam (2011).

*Environmental Conditions.* Environmental factors such as corrosion and changes in temperature that affect the condition of the structure will be estimated and taken into account in a different category. For the types of agents that maps are available such as the hazard of termite, and decay for timber bridges (Leicester et al., 2009; NAFI, 2003) their information will be used to determine and incorporate the contribution of each of them in deteriorating railway bridges in an area.

## RESULTS AND DISCUSSION

Figure 4 shows the classification proposed in this paper.

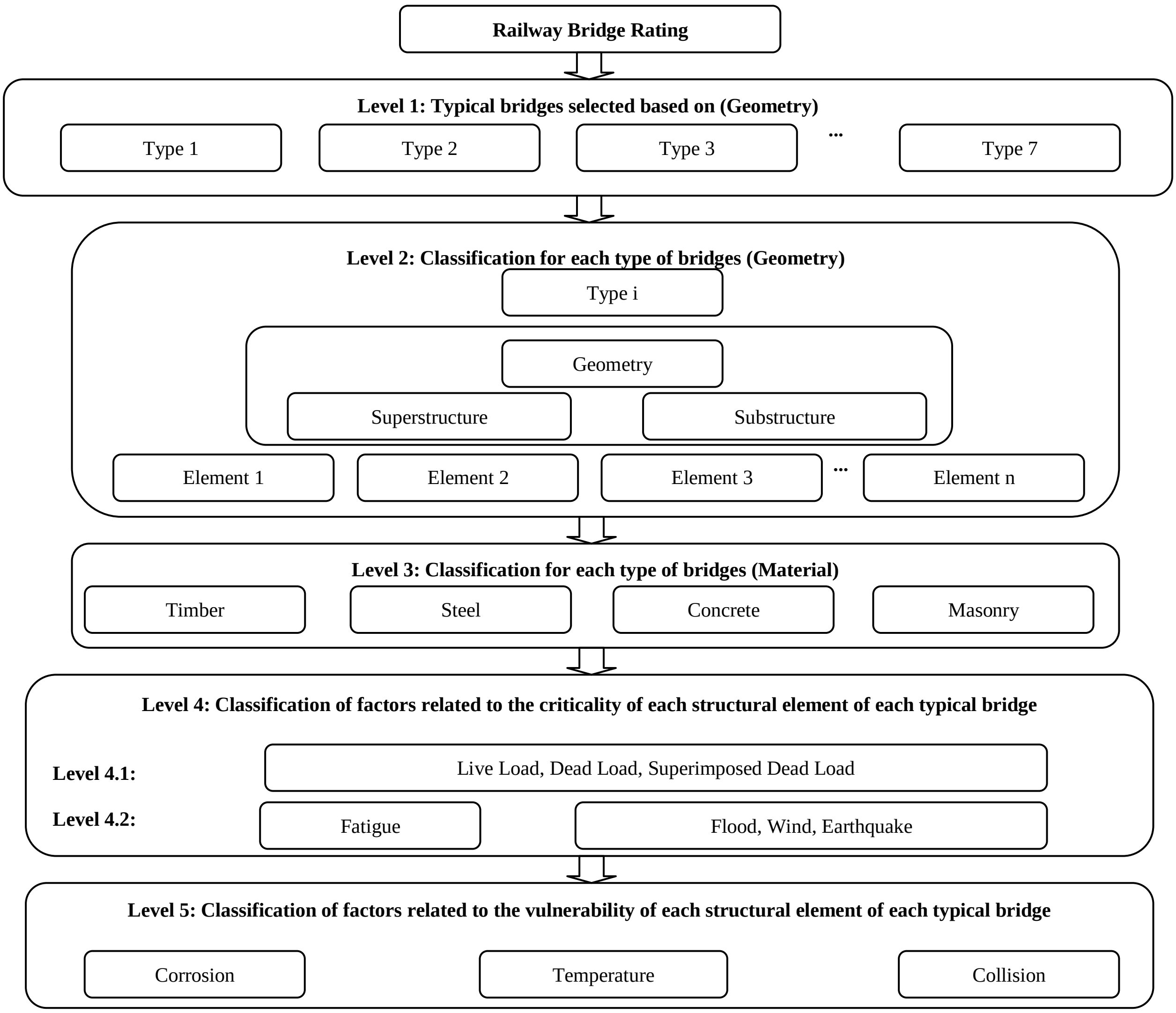


Figure 4 Railway Bridge Classification

Each element of this classification will be broken down to subcategories. It is necessary to consider loading as one element of this classification. Because, even if the structural condition of a bridge does not change after many years, the loading may change and therefore the structure may not be safe and/or serviceable.

According to this classification each individual critical structural element can be assigned a weighting factor based on the type of factor applied to the structure. That is, instead of one set of weighting factors for the critical elements of a structure, for each typical railway bridge different sets of weighting factors will be identified. Identifying typical bridges means different sets of weighting factors will be calculated separately, so the criticality of each element will be determined based on the geometry of the whole structure. In other words, based on regorous structural analysis conducted on representative bridges, the critical members will be identified by considering the loading data and strutural redandancy where weighting factors will reflect the importance of each member to the strutural intergrity in comparison point of view.

## CONCLUSION

Current practical rating systems rate bridges according to the conditions of their structural elements. Weighting factors are assigned to each element to consider the criticality of the element. However, in practice criticality has not been taken into account based on different critical factors. Recently in particular cases, it has been tried to identify critical factors and calculate the criticality of the structural elements associated with each of the critical factors. Further attempts were also made to estimate the vulnerability of the structure to predict the future condition of the bridge. However, the focus was on one bridge only or, one specific part or type of bridge and rating a network of bridges has not yet been conducted. In order to be able to take into account different factors for a variety of structures aiming at developing a rating system for a network of bridges, creating an appropriate classification is essential.

This research attempted to use and improve previous efforts to develop a new classification system which can be utilized for rating a network of railway bridges. This classification takes into account the effects of different factors on railway bridges with different geometry, material, loading, and under different environmental condition, in a systematic way to improve the accuracy of condition assessment. These effects will be taken into account by introducing weighting factors for rating bridges. The calculation of these weighting factors will be explained in details in next publication about rating railway bridges. Five different levels were defined in order to incorporate the correlation between factors such as age, condition and capacity of components, and loading.

To improve the practicality of the rating systems, a limited number of typical bridges that can represent the whole bridges in a network will be selected by this classification. Being able to improve the accuracy of rating system over time by conducting more structural analyses on more typical bridges is one of the advantages of this classification method. The other advantage of this classification is that the structural analysis will be preformed once only to determine the weighting factors, and the bridge rating process will take place based on the outcome of these analyses. Therefore, the logic of the rating system for users that will be developed based on this classification will be simple and understandable.

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