SYNTHETIC RATING SYSTEM FOR RAILWAY BRIDGE MANAGEMENT

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ABSTRACT

Railway bridges deteriorate with age. Factors such as environmental effects on different materials of a bridge, variation of loads, fatigue, etc will reduce the remaining life of bridges. Bridges are currently rated individually for maintenance and repair actions according to the structural conditions of their elements. Dealing with thousands of bridges and several factors that cause deterioration, makes the rating process extremely complicated. Current simplified but practical rating methods are not based on an accurate structural condition assessment system. On the other hand, the sophisticated but more accurate methods are only used for a single bridge or particular types of bridges. It is therefore necessary to develop a practical and accurate system which will be capable of rating a network of railway bridges. This paper introduces a new method for rating a network of bridges based on their current and future structural conditions. The method identifies typical bridges representing a group of railway bridges. The most crucial agents will be determined and categorized to criticality and vulnerability factors. Classification based on structural configuration, loading, and critical deterioration factors will be conducted. Finally a rating method for a network of railway bridges that takes into account the effects of damaged structural components due to variations in loading and environmental conditions on the integrity of the whole structure will be proposed. The outcome of this research is expected to significantly improve the rating methods for railway bridges by considering the unique characteristics of different factors and incorporating the correlation between them.

KEYWORDS

Rating Bridges, Critical Factors, Bridge Classification, Criticality, Vulnerability, Bride Management.

INTRODUCTION

Rail is one of the most important means of transport in every country and railway bridges are vital elements for them. They are designed to be serviceable for a long time. However, the structural conditions of railway bridges change over time due to environmental effects, and changes in quality and magnitude of loads (Shih et al., 2009). To remain safe and serviceable, they should be inspected and their conditions must be assessed systematically.

Due to the fact that there are thousands of them in a country and the resources are restricted, developing an appropriate Bridge Management System (BMS) is essential. A sound Bridge Management System with a minimum investment will ensure that bridges will be inspected, their condition will be assessed and timely maintenance, rehabilitation or repair actions will be conducted.

In order to assess the condition of bridges and rate them accordingly, many factors should be identified and their criticality needs to be estimated. Considering more factors increases the complexities of the structural models and consequently decreases 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 other words, to rate a group of bridges more efficiently based on their structural conditions, the current condition assessment systems of bridges should be improved.

The condition of each structural element in current practical inspection manuals is assessed during an inspection process. 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 will be assigned to them (Ryall, 2010), and finally the condition of the whole structure will be evaluated accordingly. In current practical rating systems the methods are too simplistic and may not be appropriate, as for determining these weighting factors they do not take into account many factors such as the geometry of different structures or the types of loading at a network level.

Attempts were made in current inspection manuals such as Condition Assessment of Short-line Railroad Bridges in Pennsylvania (Laman and Guyer, 2010), to incorporate the contribution of other critical factors, such as scour and fatigue, in evaluating the risk of failure. In addition, it has been tried to consider the criticality of elements subjected to particular crucial factors. However, the correlation between critical factors and critical elements of the structure has not been incorporated for developing a rating system for bridges. Although the efficiency of these rating methods increased by considering critical factors, the response of bridges with different geometry, and material, to these factors through an appropriate classification for a network of bridges still has not been taken into account.

In recent research, scholars have made significant attempt to incorporate more critical factors, in order to 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 evaluate more accurately the structural condition of Tsing Ma Bridge in Hong Kong. Xu et al. (2009) conducted criticality and vulnerability analyses and used Fuzzy Logic with AHP to develop a rating system for the Tsing Ma Bridge to deal with uncertainties from inspection process and data from the installed structural health monitoring system. AHP builds a hierarchy structure to solve a complex problem, and Fuzzy Logic is used to take into account the uncertainties associated with the inspection process and condition assessment of the bridge. Saaty (1980) developed the AHP method (Sasmal and Ramanjaneyulu, 2008), and Zahedi (1986) conducted a comprehensive investigation on the methodology of AHP and its applications. Sasmal and Ramanjaneyulu (2008) developed a multi-criteria 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 foundation. Tarighat et al. (2009) used Fuzzy Logic for rating bridges with concrete deck.

The results of the above methods based on AHP were reliable because the effects of different factors on the structure were calculated more accurately. However, they were all devised for one bridge or one type of bridge, e.g. concrete bridges, or one type of structural component of a bridge such as the foundation. In addition, Fuzzy Logic can reduce the practicality of the method if it is used for a network of bridges, as it is too complex and needs a large amount of accurate data about the bridge. Therefore, these rating systems are impractical for a network of thousands of bridges.

Structural Health Monitoring (SHM) is another method, used to detect damages and evaluate the vulnerability of the railway bridges due to environmental effects, ageing, or changes in load characteristics. This method has been developed over the last thirty years (Sohn, 2004). 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, SHM systems have been used (Li and Chan, 2006). By using SHM methods, the performance of the structure is 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). Chan et al. (2010) believe that SHM should have two components: Structural Performance Monitoring (SPM) that monitors the performance of the structure at its serviceability limit states and also Structural Safety Evaluation (SSE) that evaluates the health status by analytical tools through assessing possible damages. Recent development in SHM in Australia is summarized by Chan and Thambiratnam (2011). Despite many advantages, industry in general misconceives that SHM methods are costly and as a result, they are s not as common as they should be.

It is therefore necessary to develop a practical and economical condition assessment and rating method, which takes into account the crucial factors, and the criticality of the structural element due to different critical factors and structural configurations. Using the resources including time, expertise and equipment efficiently for improving the safety and serviceability of railway bridges will be dependent on this rating system. Reliability of this condition assessment and rating system is greatly related to the identification of critical factors, which cause deterioration of bridges.

FACTOR IDENTIFICATION

In each bridge management system, identifying the most appropriate time for intervention is very important and it depends on the prioritization method that is adopted, and the critical factors that are identified. There are many factors for prioritizing bridges such as, Train Load Frequency, Structure Age and Condition, Maintenance and Inspection Intervals, Structure Geometry and Type, Loading Factor, Resistance Factor, Condition Factor, Inspection Factor, Exposure Factor, Human Factor, Environmental Factor, Soil characteristics, Economic Factor, and factors related to deficiency functions such as, Load Capacity Function, Vertical Clearance Function and Deck Width Function (Laman and Guyer, 2010).

For rating bridges, the factors related to the probability of failure that affect the current and/or future structural condition of railway bridges are taken into account. Other factors which are predominantly related to the consequences of failure, such as economic, social, and human factors, along with the outcomes of condition assessment and rating bridges are considered for risk assessment at prioritization level to select the most economical strategies for repair and maintenance of railway bridges. To assess the condition of a bridge, all elements and factors must be identified. However, because considering all of them are costly, it is important to exclude the less important ones (Wang and Elhag, 2008). Washington State Bridge Inspection Manual (2010) names the critical elements of a structure as fracture critical elements and identifies them in different structures or structural components with different geometries such as Truss Systems, Tied Arches, and Suspension Spans. Fracture Critical Elements/Members (FCM) are those structural elements in which any failure can cause the failure of a portion or the collapse of the whole structure (Catbas, et al., 2008; Bridge Inspection Committee, 2010).

The criticality of the structural elements changes when they are subjected to different critical factors or loading. For instance, American Association of State Highway and Transportation Officials AASHTO (AASHTO, 2011) shows that spread footings are more critical than piles as they are subjected to scour and erosion. Li et al. (2002) illustrated that the impact of typhoon loading as a critical agent for fatigue damage and is more significant than traffic loading. Also Boothby (2001) shows that the critical load case and its location in a masonry arch bridge has the most severe effects on the structure. 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, sometimes can be the most critical load case for the structural components or overall structural behaviour (Catbas, et al., 2008). Weykamp, et al. (2009) identify that the criticality may be related to the significant deficiencies. They argue that critical deficiencies should be identified and eliminated before a structure reaches its critical conditions. Critical conditions that may not have effect on the structure still can cause damage such as a loose concrete that may fall on passers-by (AASHTO, 2011).

Engineers evaluate the vulnerability of a bridge after identifying the critical factors of the structure. Lind (1995) defines vulnerability as “the ratio of the failure probability of damaged system to the failure probability of the undamaged system”. Suna et al. (2010) believe that the vulnerability is the structural behaviour sensitivity to local damage. Structures can be vulnerable to some types of loads. For instance, there is a lot of research (e.g. Shamsabadi et al., 2007; Borzi et al., 2008; Polese et al., 2008), which has studied the vulnerability of 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. Corrosion, damage and wear are introduced as the vulnerability factors by Wong et al (2006).

Survey and Results

To identify critical factors for railway bridges in Australia, data for a group of about 1100 railway bridges in an urban area were collected. Some preliminary statistical analyses were then conducted on them to identify the most important factors that affect the current and future condition of railway bridges. Figure 1 shows that more than 70% of these railway bridges are more than 40 years old. This means, they may require maintenance or repair. In addition, steel was identified as the main material that was used in superstructure components of railway bridges. Therefore, the effect of corrosion and fatigue will be the most critical factor for the durability of bridges.

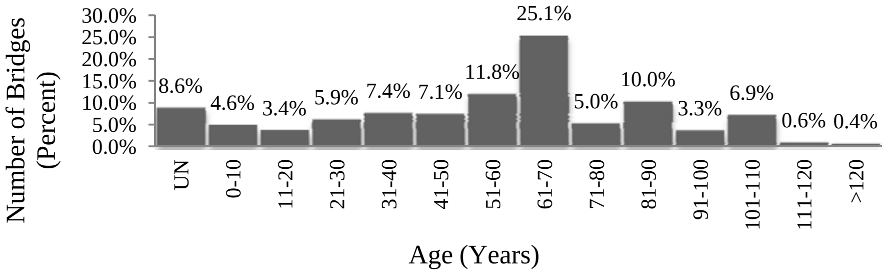

Figure-1 Age of railway bridges in a sample of 1122 in Australia

The analyses of the data also show that the inspection process should be focused on spread footings, as they are used much more frequently than piles (Figure 2). In addition, the materials of about 45% of the foundations of railway bridges have not been identified through an inspection process (Figure 3). Therefore, it can be concluded that the accessibility to these structural elements are very limited and consequently the type of questions that are 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 the deterioration of railway bridges and decreasing their remaining service life in Australia.

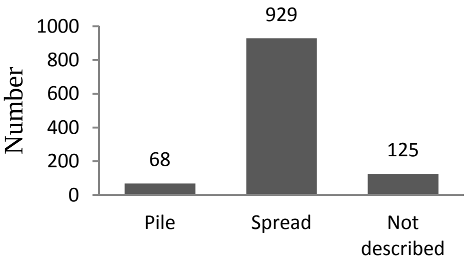

Figure-2 Foundation Type

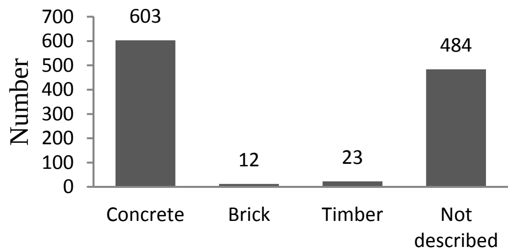

Figure-3 Foundation Material

SYNTHETIC RATING METHOD

This section will explain and describe the methodology and formulation of the proposed Synthetic Rating System. This rating system is devised to tackle the shortcomings found through the above survey and investigations. The calculations of the weighting factors and determining the priorities of different critical factors will be conducted and reported later in another paper based on the methodology and mathematical equations that will be described here.

As mentioned earlier, to develop an accurate and practical method for rating bridges, the criticality of the structural elements for the integrity of different types of bridges due to different critical factors should be determined. To this purpose a classification system which considers the geometry of the structure, environmental conditions that affect the durability of the bridge, structural materials and type of bridges is proposed in this research as shown in figure 4. The purpose of developing this classification was to take into account the criticality of factors based on their unique characteristics and the effects that they have on current and future conditions of railway bridges, in order to be able to compare and rate a network of bridges. The outcome of this rating system, which is based on the structural condition of bridges, along with other factors that will be used to estimate the consequences of failure, will be utilized for risk assessment and prioritisation of bridges within a Bridge Management System.

To avoid modelling thousands of railway bridges in a network level, typical bridges each of which represents a group of similar railway bridges have been identified (Table 1), in order to calculate the level of criticality for each structural element and for each type of these typical bridges. Each of the elements of this classification will be broken down to subcategories. It is necessary to consider loading as one of the 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.

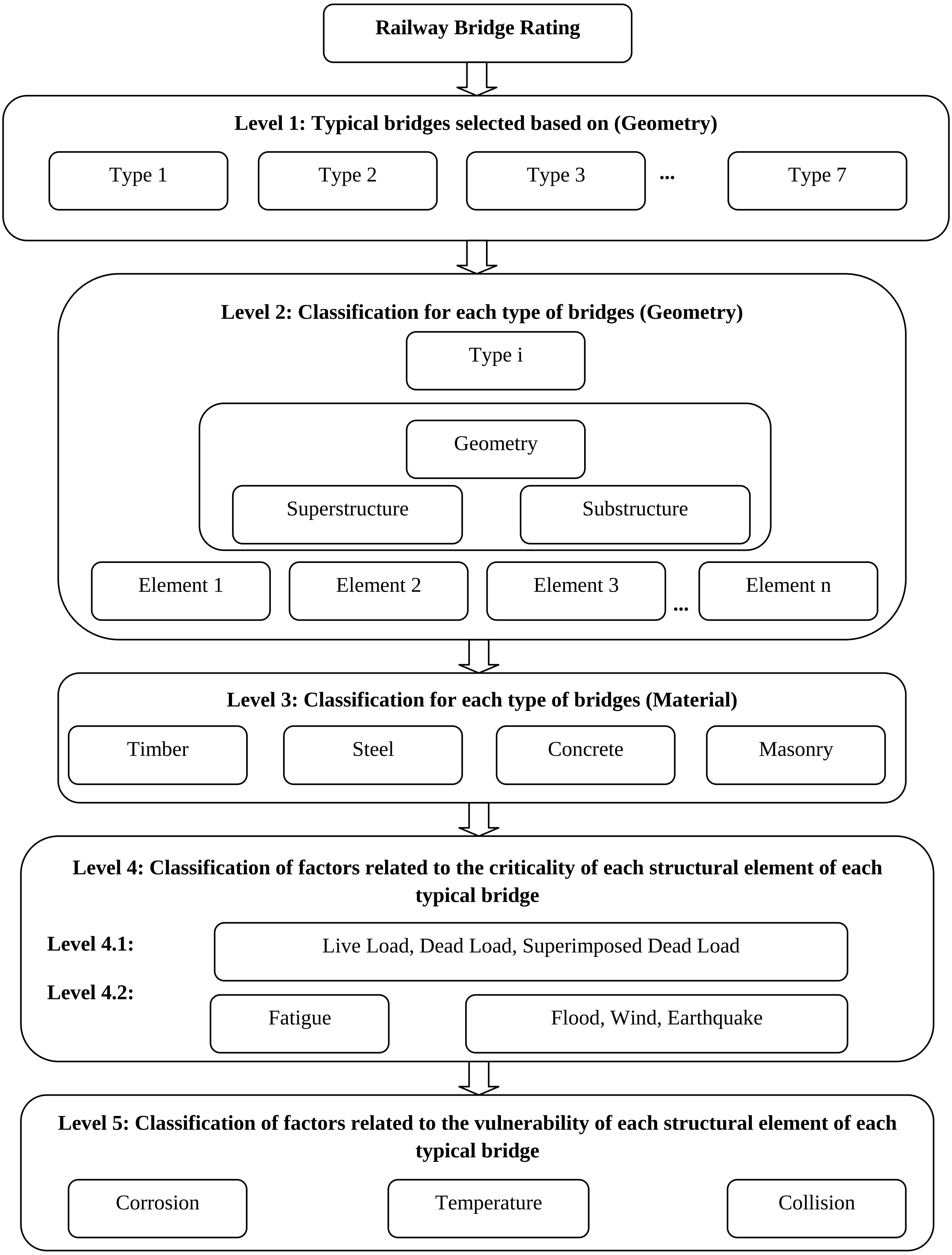

Figure-4 Railway Bridge Classifications

Table-1 Typical Railway Bridges and their components

Bridge Type	Bridge Components		
Type 1: Simply Supported	Foundation	Abutments	Back wall
	Wing walls	Piers	Columns
	Primary Beams	Secondary Beams	Deck
	Joints		
Type 2: Continuous Supported	Foundation	Abutments	Back wall
	Wing walls	Piers	Columns
	Primary Beams	Secondary Beams	Deck
	Joints		
Type 3: Rigid Frame	Foundation	Abutments	Back wall
	Wing walls	Piers	Columns
	Primary Beams	Secondary Beams	Deck
	Joints		
Type 4: Arch 1	Foundation	Abutments	Back wall
	Wing walls	Piers	Columns
	Spandrel columns	Primary Beams	Secondary Beams
	Arch	Deck	Joints
Type 5: Arch 2	Foundation	Abutments	Back wall
	Wing walls	Piers	Columns
	Spandrel columns	Primary Beams	Secondary Beams
	Arch	Deck	Joints
Type 6: Arch 3	Foundation	Abutments	Back wall
	Wing walls	Piers	Columns
	Spandrel columns	Primary Beams	Secondary Beams
	Arch	Deck	Joints
Type 7: Truss	Foundation	Abutments	Back wall
	Wing walls	Piers	Columns
	Primary Truss	Secondary Beams	Deck
	Joints		

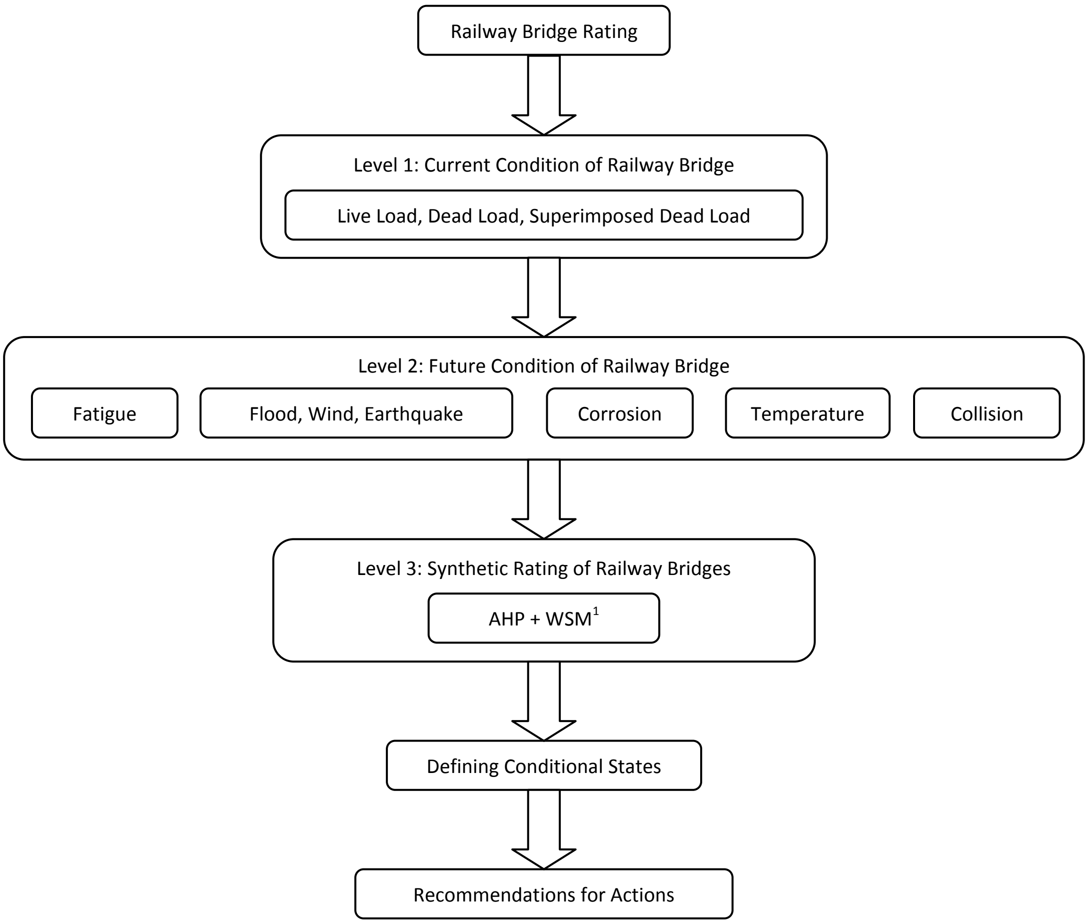

Figure-5 Synthetic Rating Algorithm for each Type of Bridges

The importance of each critical factor is calculated based on AHP method and through calculating the eigenvalues and eigenvectors of the pair-wise matrixes. The weighting factors are estimated by conducting structural analyses, and the load combinations factors and the risk of their occurrence according to Australian standards. Figure 5 shows the algorithm for the proposed synthetic rating system.

Different conditional states can be defined by identifying the acceptance level and the rating results associated with the structural condition of the bridge. These conditional states can be used to propose recommendations for inspection frequency and type, estimating the remaining service life of the bridge, intervention for maintenance and repair actions. Furthermore, recommendations for using equipment for more detailed inspection, or monitoring the health condition of the important railway bridge structures can be made.

CONDITION RATING FOR BRIDGE MANAGEMENT

Based on the classification in figure 4 and the developed algorithm in figure 5, the condition of a Type 1 bridge can be obtained from Eq. 1. The following equations were developed based on WSM[1], AHP and rating methods mentioned in this paper.

$$BC = \Upsilon_1 BCC + \Upsilon_2 BFC \qquad \text{Eq. 1}$$

where,

BC is the value that reflects the current and future condition of the bridge, and rating of railway bridges will be conducted based on that.

Υ_1, Υ_2: Coefficients that will be determined for decision making based on management's factors

BCC and *BFC* could be obtained from Eq. 2 and Eq. 3 respectively.

$$BCC = \alpha_l \sum_{i=1}^{n} C_{ci} al_i + \alpha_{fa} \sum_{i=1}^{n} C_{ci} afa_i + \alpha_{fl} \sum_{i=1}^{n} C_{ci} afl_i + \alpha_w \sum_{i=1}^{n} C_{ci} aw_i + \alpha_e \sum_{i=1}^{n} C_{ci} ae_i \qquad \text{Eq. 2}$$

where,

BCC: Bridge Current Condition

n: Number of Components

α_l, α_{fa}, α_{fl}, α_w, α_e: Coefficients that respectively shows the importance of Live load, Fatigue, Flood load, Wind load and Earthquake load as defined in Table 2 and it will be determined through AHP method

al_i, afa_i, afl_i, aw_i, ae_i: Weighting factors associated with component i that are respectively related to Live load, Fatigue, Flood load, Wind load and Earthquake load as defined in Table 2 and it will be determined structural analysis

C_{ci}: Current condition of the ith component identified form inspection (a number from 1 to 5)

$$BFC = \beta_{cor} \sum_{i=1}^{n} C_{fi} bcor_i + \beta_t \sum_{i=1}^{n} C_{fi} bt_i + \beta_{col} \sum_{i=1}^{n} C_{fi} bcol_i \qquad \text{Eq.3}$$

where,

BFC: Bridge Future Condition

n: Number of Components

β_{cor} , β_t , β_{col}: Coefficients that respectively shows the importance of Corrosion, Changes in Temperature, and Collision as defined in Table 3, and it will be determined through AHP method

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[1] Weighted Sum Model (WSM) (Triantaphyllou et al., 1997; Sasmal and Ramanjaneyulu, 2008)

$bcor_i$, bt_i , $bcol_i$: Weighting factors associated with component i that are respectively related to Corrosion, Changes in Temperature, and Collision as defined in Table 3, and it will be determined by prediction of deterioration rate equations and Remaining Service Potential

C_{fi}: Future condition of the ith component identified by the prediction of deterioration rate equations and Remaining Service Potential (a number from 1 to 5)

Table-2 Weighting Factors for Type one Bridges related to the current condition assessment

	Component	Current Component Condition	Weight (Live Load)	Weight (Fatigue)	Weight (Flood)	Weight (Wind Load)	Weight (Earthquake)
1	Foundation	C_{c1}	al_1	afa_1	afl_1	aw_1	ae_1
2	Abutments	C_{c2}	al_2	afa_2	afl_2	aw_2	ae_2
3	Back wall	C_{c3}	al_3	afa_3	afl_3	aw_3	ae_3
4	Wing walls	C_{c4}	al_4	afa_4	afl_4	aw_4	ae_4
5	Piers	C_{c5}	al_5	afa_5	afl_5	aw_5	ae_5
6	Columns	C_{c6}	al_6	afa_6	afl_6	aw_6	ae_6
7	Primary Beams	C_{c7}	al_7	afa_7	afl_7	aw_7	ae_7
8	Secondary Beams	C_{c8}	al_8	afa_8	afl_8	aw_8	ae_8
9	Deck	C_{c9}	al_9	afa_9	afl_9	aw_9	ae_9
10	Joints	C_{c10}	al_{10}	afa_{10}	afl_{10}	aw_{10}	ae_{10}
Bridge Current Condition (BCC)			BCL	BCFA	BCFl	BCW	BCE

Table-3 Weighting Factors for Type one Bridges related to the future condition assessment

	Component	Future Component Condition	Weight (Corrosion)	Weight (Temperature Changes)	Weight (Collision)
1	Foundation	C_{f1}	$bcor_1$	bt_1	$bcol_1$
2	Abutments	C_{f2}	$bcor_2$	bt_2	$bcol_2$
3	Back wall	C_{f3}	$bcor_3$	bt_3	$bcol_3$
4	Wing walls	C_{f4}	$bcor_4$	bt_4	$bcol_4$
5	Piers	C_{f5}	$bcor_5$	bt_5	$bcol_5$
6	Columns	C_{f6}	$bcor_6$	bt_6	$bcol_6$
7	Primary Beams	C_{f7}	$bcor_7$	bt_7	$bcol_7$
8	Secondary Beams	C_{f8}	$bcor_8$	bt_8	$bcol_8$
9	Deck	C_{f9}	$bcor_9$	bt_9	$bcol_9$
10	Joints	C_{f10}	$bcor_{10}$	bt_{10}	$bcol_{10}$
Bridge Future Condition (BFC)			BCOR	BCT	BCOL

For other types of railway bridges the formulation are the same, but the weighting factors and coefficients will change and will be discussed in separate papers.

This method will help to avoid transferring the sophistication of the process to practice, by conducting detailed structural analysis once only, to determine the set of weighting factors for each type of railway bridges. The calculation of the weighting factors will be conducted and reported in another paper.

CONCLUSIONS

The condition assessment and rating of railway bridges are critical for every BMS and can be improved with a series of equations, Eq.1-3. These equations have included the critical factors of structural configuration, loading, and environmental effects (refer figure 4). Critical factors have been weighted to simplify the calculations and make it more practical for end users. One group of weighting factors shows the criticality of each structural component for the integrity of the whole structure. The other represents the importance of different critical factors for the current and future conditions of bridges.

As conducting structural analysis on each individual bridge in a network of thousands of railway bridges is impractical and costly, typical bridges were identified where each represents a group of bridges with similar structural configurations. For each typical bridge the first group of weighting factors associated with the critical elements was taken into consideration. This new rating method has the capacity to be improved in the future with the on-going enrichment of the database of the BMS, as well as conducting further structural analyses and identifying more typical bridges.

Improving the accuracy of this rating system is dependent on 1) taking into account the critical factors, 2) considering the correlation between critical factors and critical structural components, and 3) assessing the vulnerability of the structure based on them. The increased accuracy, does not make the rating system more complex and its practicality is preserved. This rating system will lead to more appropriate inspection procedures as well as condition evaluation of bridges more reliably. It will also determine the best time to intervene for maintenance or repair actions. Managers and project planners can use this rating system to invest resources more efficiently and consequently improve the safety and serviceability of railway bridges.

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