A Novel Method for Quantifying the Criticality and Vulnerability of the Components of Railway Bridges

M. Aflatooni*, T.H.T Chan*, and D.P. Thambiratnam*

* School of Civil Engineering and Built Environment, Science and Engineering Faculty
Queensland University of Technology, George St, Brisbane, Queensland, 4001, Australia
(E-mail: m.aflatooni@qut.edu.au)

Abstract

Conditions of bridges deteriorate with age, due to different critical factors including, changes in loading, fatigue, environmental effects and natural events. In order to rate a network of bridges, based on their structural condition, the condition of the components of a bridge and their effects on behaviour of the bridge should be reliably estimated. In this paper, a new method for quantifying the criticality and vulnerability of the components of the railway bridges in a network will be introduced. The type of structural analyses for identifying the criticality of the components for carrying train loads will be determined. In addition to that, the analytical methods for identifying the vulnerability of the components to natural events whose probability of occurrence is important, such as, flood, wind, earthquake and collision will be determined. In order to maintain the practicality of this method to be applied to a network of thousands of railway bridges, the simplicity of structural analysis has been taken into account. Demand by capacity ratios of the components at both safety and serviceability condition states as well as weighting factors used in current bridge management systems (BMS) are taken into consideration. It will be explained what types of information related to the structural condition of a bridge is required to be obtained, recorded and analysed. The authors of this paper will use this method in a new rating system introduced previously. Enhancing accuracy and reliability of evaluating and predicting the vulnerability of railway bridges to environmental effects and natural events will be the significant achievement of this research.

Keywords

Rating Bridges, Flood, Collision, Earthquake, Wind, Criticality, Vulnerability, Environmental effects

Introduction

In every bridge management systems (BMS), one of the main tasks is to assess the condition of bridges and identify those, which damaged most. To evaluate the condition of a bridge, engineers pay special attention to the critical components of the bridge and vulnerability of them to different critical factors. Critical factors include live load, flood, earthquake, and wind loads, collision and environmental effects [1]. Any failure of these components has significant impact on the load carrying capacity and serviceability of the bridge. This paper will focus on identifying the methods for estimating the criticality and vulnerability of components of the railway bridges. At network level, because there could be thousands of railway bridges for condition assessment, the method for identifying the criticality of the components should be simple to make the method practical; however, it should be reliable as well.

The criticality of the components will be identified by assigning weighting factors to them [2]. For determining weighting factors in practical methods for rating a network of bridges such as VicRoads [3] or New York methods [2], the structural configuration of bridges is not taken into account. In addition, they cannot reliably anticipate the future condition of the bridge, as in calculation of weighting factors according to their rating methods, the vulnerability of the components towards critical factors are not taken into consideration. In these methods, for the sake of practicality the reliability of the method decreases. Other methods such as those introduced by Wong [4] or Xu et.al [5], are based on criticality and vulnerability analyses and use structural health monitoring system (SHM) to determine the condition of a particular large bridge (Tsing Ma Bridge in Hong Kong). Their methods are far more reliable, but because of complexity, are not practical to be applied to a network of bridges. Through SHM methods the performance of the bridge is monitored and the safety of the bridge is evaluated [6]. The book edited by Chan and Thambiratnam [7] shows recent developments in SHM methods in Australia.

Therefore, according to literature, the methods for condition assessment of bridges are either practical to be applied to a network of bridges but not reliable or reliable but not practical to be applied to a network of bridges. In this paper a method is introduced to find weighting factors for components. According to this method, in order to estimate the weighting factors, Demand by Capacity (D/C) ratios of the components when the structure is subjected to different loads is calculated. Demand means stresses induced in the components due to applied loads to the structure. The capacity means the strength of the component to the loads applied to them. In addition, the effects of the structural details, and non-structural components on the safety and serviceability of the structure are taken into account. These weighting factors are used in a practical and reliable rating method developed by Aflatooni et.al. [8] for condition assessment and rating bridges. Through increasing the reliability of condition assessment of a network of railway bridges, resources will be efficiently invested to improve the safety and serviceability of them.

Criticality and Vulnerability of Components

As mentioned earlier the current adopted practical methods are not reliable, and they cannot answer to the key question that whether the capacity of the current bridges is adequate to carry train loads. The reason is that, to consider the criticality of the component, they do not take into account the structural configuration of the railway bridges. Conducting structural analyses to identify weighting factors, which reflect the criticality of components for the integrity of the structure and vulnerability of the components to critical factors, will be inevitable. However, this analytical method should be simple; otherwise, they would not be practical to be applied to a network of thousands of railway bridges.

To reduce the consumption of the resources, including expertise, time and computing machines, the structural analyses procedures should be sufficiently simple, to be performed by a junior engineer with a limited supervision of a senior engineer. Frequently performing structural analyses on thousands of bridges is not practical; as a result, it has been identified that the structural analyses can be conducted every 6 years or when the structural condition exceeds some specific safety thresholds. These thresholds will be discussed in our next publications. The majority of the railway bridges at network level are simple structures with low level of redundancies. Therefore, conducting alternative load path analyses 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 analysis similar to the work conducted by Wong [4] or Xu et.al [5] may be only performed on special bridges, which have a high amount of degrees of freedoms or being a significant or critical structure at the network level. The number of these types of bridges is limited, and study of them is out of the scope of this research.

Considering the above explanations about the practicality of the analytical methods for determining the weighting factors, the calculation of the D/C ratios of the structural components of the bridge is introduced. These calculations provide an appropriate understanding about the real performance of the railway bridges. Although because of bridge deterioration, the components loss their capacities; many of them still can safely carry loads, as they may be overdesigned. Therefore, D/C ratios of components can show their criticality to carry live load and vulnerability of them towards critical factors such as environmental effects, flood, earthquake, wind, and collision.

Weighting factors should be calculated at both safety and serviceability levels. Components of a railway bridge are placed in 3 categories, including 1) structural components, 2) none-structural components and 3) structural details. At safety level, the D/C ratios of the structural components are calculated at ultimate limit state (ULS), and considered as weighting factors of the structural components. For non-structural components, consequences due to any failure in them should be investigated to calculate weighting factors of each components, associated with different critical factors. For structural details, their criticality should be identified based on the effect of any changes in their condition 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 serviceability limit state (SLS), changes in the condition of the structural, non-structural and structural details are taken into account to determine the criticality and vulnerability of the components. The criticality and vulnerability of the structural component will be calculated through separately applying different loads including, live load, flood, wind, collision, and earthquake at SLS and calculating the D/C ratios. For non-structural components, and structural details, the consequences due to any damages in them or changes in their condition on the serviceability should be estimated. This estimation should be conducted through recording the cost associated with the malfunctioning of the bridge in the long run to be able to reliably evaluate the criticality or vulnerability of the none-structural components.

At this stage, because adequate investigations on the consequences of failure at both the safety and serviceability levels on none-structural components and structural details have not been conducted, the weighting factors used by BMSs such as VicRoads [3] can be utilized for all critical factors. 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.

<u>Live load</u>

The live load is the most important load, as the aim of a bridge is to carry this load. Making decision about the condition of the components, only based on the inspection reports is not appropriate. As explained before, D/C ratio of the components are used to identify the weighting factors. 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 bending and axial forces.

To calculate the demand, a combination of dead and live load is taken into account. Safety factors are not applied to these loads, because these structures have been designed based on previous outdated standards, hence they cannot meet the current design standards requirements. 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 [9], AS 3600 [10], AS 4100 [11] etc, as well as inspection records related to the current condition of the structural components are used. Other countries may use their local design codes.

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 should be a number between 0 to 1. Numbers higher than one means the component failed, and cannot carry loads. Higher numbers in the range of zero to one shows more criticality of the condition of the components. In order to quantify these criticalities, engineers shall also take into account the susceptibility of the component to the increase of load through conducting dynamic analysis. Because, according to Aflatooni et.al [12] investigation, resonant vibration can have significant impact on the D/C ratios of the components.

<u>Flood</u>

In order to identify the vulnerability of the bridge and its components, the combination of dead and flood load is considered. The D/C will be calculated at both ULS and SLS, and the weighting factors related to the vulnerability of the structural component will be estimated. According to AS 5100.2 [13], the forces applied to the railway bridges due to a flood include: drag forces on piers, lift forces on piers, drag force on superstructure, lift force on superstructures, moment on a superstructure, forces due to debris on sub and super structures, and forces due to log impact. In every country, local relevant codes or standards can be used to calculate the above forces.

Collision

Collision here refers to the vehicle impact. Ship impact is not applicable to the types of railway bridges considered in this research. For collision, only ULS is used to calculate the D/C ratio. Because the SLS is not applicable for collision. Collision loads and its direction can be obtained from AS 5100.2 [13]. If the protection beam or barriers are capable to resist the collision loads, the vulnerability assessment is not required.

Earthquake

Although, according to the expert opinion the cost associated with the damages due to earthquake is not considerable in Australia, in many parts of the world, earthquake is one of the critical factors in damaging railway bridges. Therefore, for the parts of the world that this extreme event significantly contributes in railway bridge deterioration, engineers should conduct structural analysis. For life cycle bridge management and estimating the cost of maintenance and repair, they need to perform these analysis at both safety and serviceability levels. For the railway bridges, which their substructures significantly damaged, nonlinear analysis may need to be conducted.

In Australia if engineering studies show that some railway bridges and in some particular areas can be considerably affected by earthquake, standards such as AS 1170.4 [14] and AS 5100.2 [13] along with design standards can be used for estimating earthquake effects on the structure. Respectively, ULS and SLS forces should be applied to the railway bridge to calculate the D/C ratios in structural components at safety and serviceability levels. These ratios are used as weighting factors for ULS and SLS. Dead and earthquake loads are taken into account to calculated the demand forces in this section.

Wind

To calculate the D/C ratios of components related to wind load and obtaining weighting factors associated with them in Australia, AS 1170.2 [15], and AS 5100.2 [13] along with design standards 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. A combination of dead and wind loads is applied to the structure.

Environmental factors and fatigue

For the environmental effects and fatigue, the weighting factors assigned to live load is used. Environmental factors includes many different agents, 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 of them are inter-related. Although, the effect of fatigue is different in respect to environmental factors as it happens because of cyclic loads, they are similar as both gradually degrade the structure over a long period.

It will be recommended to conduct investigations on fatigue or even each individual environmental factor, to calculate separate set of weighting factors for each of them. These investigations shall 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 very reliable methods for predicting the future condition of the components, such as probabilistic methods, are the reasons for using live load weighting factor for them.

Conclusion

Study of the literature shows that the current methods for condition assessment of railway bridges, which are practical to be used for a network of thousands of bridges are not adequately reliable. The reason is that, in calculating the criticality and vulnerability of the components, they do not take into account the structural configuration of different railway bridges, and the effect of different critical factors. On the other hand the methods which determine the criticality and vulnerability of the components based on different critical factors, are too complex and not practical to be applied to a network of bridges.

In this paper, a method for estimating the criticality and vulnerability of the components of a railway bridge was introduced which is practical to be applied to a network of railway bridges. Based on this method, components of a railway bridge are placed in 3 categories, including structural, non-structural components and structural details. D/C ratios of the components when the structure is subjected to different critical factors at both ULS and SLS, are calculated and used as the weighting factors. These weighting factors show the criticality and vulnerability of the components of the structure. At this stage, weighting factors available in current railway agencies are used for non-structural components and structural details for which adequate data on the condition of the bridge is not available and sufficient investigations have not yet been carried out. However, it will be recommended to provide technical records and conduct investigations on the consequences of failure associated with each specific critical factor, at both safety and serviceability levels. As a result, different weighting factors for each non-structural component or structural details related to different critical factors can be calculated.

The unique contribution of the proposed method is the incorporation of structural analysis in condition assessment of bridges in a practical way. According to this method, instead of assigning a single weighting factor to one component type e.g. column of all bridges without conducting any structural analyses, a set of weighting factors is assigned for each single component of each individual bridge. This set of weighting factors is evaluated by considering the action of different loads acting on the bridge. In other words, for one single beam of one specific bridge, five weighting factors related to live load, flood, collision, wind, and earthquake will be calculated through structural analyses under both safety and serviceability levels. This will enable the safety of the bridge for carrying live load and its vulnerability to each extreme event, including flood, wind, collision and earthquake, to be estimated in a reliable way. Calculating and applying the demand to capacity ratios of the components, their true capacities and hence the true performance of the structure are taken into account.

To improve the practicality of the method, performing the structural analyses has been limited to every six years for most cases. Alternative load path analysis may not be conducted as the majority of the bridges at network level have simple structures with limited number of components. A failure in any of them can hence significantly decrease the safety of the bridge. In other words, all the structural components are important, and conducting alternative load path analysis only makes the method complex and costly, and impractical to be applied to the network of bridges.

Through using this method for identifying the criticality and vulnerability of the components in the synthetic rating method developed by the authors of this paper, the criticality and vulnerability of the components of a railway bridge and the weighting factors associated with them, can be reliably identified. As a result, engineers can evaluate the current and future condition of the railway bridges and be capable of efficiently investing the resources towards bridge safety and serviceability.

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