Structural Monitoring and Maintenance, *Vol. 2, No. 3 (2015) 199-211*
DOI: http://dx.doi.org/10.12989/smm.2015.2.3.199

Condition monitoring and rating of bridge components in a rail or road network by using SHM systems within SRP

Mehran Aflatooni*, Tommy H.T Chan[a] and David P. Thambiratnam[b]

School of Civil Engineering and Built Environment, Science and Engineering Faculty, Queensland University of Technology, Brisbane, Queensland, Australia

(Received March 12, 2015, Revised August 9, 2015, Accepted August 17, 2015)

Abstract. The safety and performance of bridges could be monitored and evaluated by Structural Health Monitoring (SHM) systems. These systems try to identify and locate the damages in a structure and estimate their severities. Current SHM systems are applied to a single bridge, and they have not been used to monitor the structural condition of a network of bridges. This paper propose a new method which will be used in Synthetic Rating Procedures (SRP) developed by the authors of this paper and utilizes SHM systems for monitoring and evaluating the condition of a network of bridges. Synthetic rating procedures are used to assess the condition of a network of bridges and identify their ratings. As an additional part of the SRP, the method proposed in this paper can continuously monitor the behaviour of a network of bridges and therefore it can assist to prevent the sudden collapses of bridges or the disruptions to their serviceability. The method could be an important part of a bridge management system (BMS) for managers and engineers who work on condition assessment of a network of bridges.

Keywords: synthetic rating procedures, structural health monitoring systems, strain gauges, deflection sensors, bridge management systems, criticality and vulnerability assessment

1. Introduction

Development of a reliable method for continuously monitoring the condition of a network of bridges is one of the essential needs of a bridge management system (BMS). BMSs are developed to maintain the safety and serviceability of a network of bridges. An important part of a BMS is to prioritise bridges based on their structural condition. The structural condition of a bridge is determined based on the condition of its important components. The condition of a component is deteriorated over time due to ageing and loading. Due to the scarcity of resources which are allocated to repair and maintain the components, they should only be invested on bridge components which their structural conditions are worse than others in a network of bridges. Hence, continually identifying those components with worst condition and rating them accordingly is an essential part of a BMS. Aflatooni (2015) attempted to critically review the literature related to bridge management and rating systems where further information could be found.

---

*Corresponding author, Ph.D., E-mail: m.aflatooni@qut.edu.au
[a] Professor, E-mail: tommy.chan@qut.edu.au
[b] Professor, E-mail: d.thambiratnam@qut.edu.au

http://www.techno-press.org/?journal=smm&subpage=7 ISSN: 2288-6605 (Print), 2288-6613 (Online)

Continual condition assessment of a network bridges and evaluate their behaviour, assists managers and engineers to prevent the sudden collapses of bridges and take appropriate preventative actions. Through continuous real time monitoring of structures, the best time for conducting maintenance and repair is identified, and applying unnecessary restrictions on the usage of bridges are avoided. Aflatooni (2015) developed a synthetic rating method for rating a network of bridges which includes the synthetic rating procedures (SRP). SRP is based on the criticality and vulnerability assessment of each bridge and its components in a network, and evaluating their safety and serviceability to different loads (Aflatooni *et al*. 2014). It includes the current and future conditions of bridges. According to SRP, the criticality and vulnerability assessment of the bridges' components and evaluating their current and future safety and serviceability to different loads are conducted based on structural analysis. In this paper, a method will be proposed to use SHM system and the structural analysis to monitor the current condition of bridges to the loads applied to the structure. This method will be used within the SRP and provide more information for it about the current condition of bridges through online monitoring their behaviour. The proposed method will not be used for the future condition of bridges hence for future condition, the outcome of the structural analysis explained in SRP will be used.

SHM systems are used for continuous evaluation of the safety and serviceability of a bridge or its components. Currently they are only used for a single bridge or a component of a bridge. It is therefore, necessary to extend the application of this valuable tool to the condition assessment of a network of bridges. SHM systems are developed to detect and locate the damages in a bridge. Researchers have conducted many studies on SHM over the last two or three decades (Chan and Wang 2013, Sohn 2004, Wang *et al*. 2013). 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). In Australia many studies on SHM systems and their publications have been carried out (Chan and Wang 2013, Chan and Thambiratnam 2011).

SHM systems utilize a group of sensors to measure the responses of a bridge, and then adopt an algorithm to interpret the measurements and evaluate the structural condition of a bridge (Liang *et al.* 2001). Chan *et al*. (2011) provide information about different sensors used in a SHM system for loads and responses measurements. Chan *et al*. (2011) believe that SHM systems should have two components: structural performance monitoring (SPM) that monitors the performance of the structure at its serviceability limit states, and structural safety evaluation (SSE) that evaluate the health status by analytical tools through assessing of possible damages. According to Li *et al*. (2009) an ideal health monitoring system should identify the damage, shows its location, determine the type of the damage and its severity and finally its impact on the behaviour of the civil structures.

In vibration based SHM systems, the health of a bridge or its components are evaluated based on monitoring some characteristics of the structure such as natural frequency, mode shapes, and modal damping values (Radzieński *et al*. 2011, Salawu 1997). Those characteristics are identified through experimental or field tests. In addition, researchers use modal derivatives such as modal flexibility, mode shape curvatures, and modal strain energy for damage detection or localisation (Catbas *et al.* 2008, Roy and Ray-Chaudhuri 2013, Shih *et al*. 2009, Wang 2012). Frequency response function (FRF) are also used by some researchers for damage detection (Bandara 2013, Sampaio *et al.* 1999). In order to properly analyse the mode shapes tools such as wavelet transform (Taha *et al*. 2006), neural networks (Bandara *et al*. 2014, Lee *et al*. 2005), least-squares estimation approach (Yang and Lin 2005), linear matrix inequality (Abdalla *et al.* 2000), multi-criteria non-linear optimisation (Hassiotis 2000), and genetic algorithm (Nobahari and Seyedpoor 2011, Wang 2012) are also incorporated in the damage detections techniques. In addition, structural model updating was another technique used by researchers to detect damage in a structure (Reynders *et al.* 2010, Wu and Li 2006).

One of the responses of the structure which are used to identify the stresses in a component is the strains in critical locations of a component. Measurement of strains in critical locations can determine whether the forces applied to the component is larger than its capacity. The strains are measured by strain gauges. There are different types of strain gauges such as electrical resistance strain gauges, vibrating wire strain gauges, and fibre bragg grating (FBG) (Chan *et al.* 2006, Ko and Ni 2005). To select an appropriate strain gauge the requirements such as accuracy, temperature, stability, duration of usage, and cyclic endurance should be taken into account (Micro measurements a VPG Brand 2014). Some of the parameters which affect the operation of a strain gauge are its strain-sensing alloys, gauge pattern, grid resistance and backing materials (Micro measurements a VPG Brand 2014). The strain gauges are used for measuring the responses of both steel and reinforced concrete components (Bao *et al.* 2001, Henault *et al.* 2012). Researchers use strain gauges to estimate the remaining fatigue life of a bridge (Li *et al.* 2003, Zhou 2006).

Vertical displacement of components is another important response for evaluating the serviceability of a bridge or its components. The vertical displacement can be determined through different methods (Chan *et al.* 2009, Yau 2014). Some techniques used for measuring the vertical deflection of a component are terrestrial laser scanning (TLS), linear variable displacement transducers (LVDTs), electric strain gauges, and using fibre optic sensors (Chan *et al.* 2009, Park *et al.* 2007, Yau 2014). Vertical displacement of components can also be measured directly by using methods such as surveying, using global positioning systems (GPSs) (Ogundipe *et al.* 2014), and photogrammetric measurements (Jáuregui *et al.* 2003). The accuracy of measuring the vertical deflection through the preceding methods can be affected by different factors such as atmospheric or weather condition. The vertical displacement can also be determined indirectly through calculating the curvature of different points of a component (Vurpillot *et al.* 1996, Yau *et al.* 2013). Geometry of a component and boundary condition are some of the important factors which should be taken into account while the vertical displacement is calculated through indirect methods.

The SHM systems explained above collect detailed responses of a structure or a component of a structure and conduct comprehensive analysis to investigate their structural behaviour or health. Although in many cases they can be applied to a specific bridge or a component, they should be simplified to be applied to a network of bridges, as the complexity of the structural behaviour of a network of bridges are very high. Therefore, this paper focuses on collecting the type of data which directly reflect the safety and/or serviceability of structures. The method will be used to provide more additional information for SRP about the current condition of a network of bridges. The method can significantly increase the efficiency of using the scarce resources which are invested on maintaining bridges.

2. Proposed method for continual health monitoring and rating of the components of a network of bridges

This section describes a new method which will be used in synthetic rating method and SRP for condition assessment and rating of the components of a network of bridges based on their current condition. According to SRP, the criticality and vulnerability of the components are determined based on the demand by capacity ratios (DCRs) of the components. The criticality and vulnerability of the current condition of the components at both safety and serviceability levels can either be identified by structural analysis or measuring the responses of the structure through utilizing SHM systems. The demand means the responses of a component of a structure including deflections, and internal strains or stresses induced by different loads including vehicle dynamic load, flood, wind, earthquake, and collision loads. The capacity of a component is the maximum responses that a component is allowed to have based on design standards, when the structure is subjected to any of the previously mentioned loads. The calculation of DCRs of components by using structural analysis can be seen in the authors' previous publications (Aflatooni 2015, Aflatooni *et al*. 2014, Aflatooni *et al*. 2015).

A bridge in a network of bridges may be subjected to different loads including live (vehicle) load, wind, flood, earthquake, and collision. The developments in measuring the responses of structures though new devices can help engineers to directly and reliably evaluate their condition without conducting structural analysis. In order to assure that a component will not fail under a particular of load, the engineers need to determine that in any critical locations of the component, the strain will not exceed the maximum strain that the component can carry. Similarly, for serviceability of the structure they have to be ascertained that the maximum deflection of any components of the bridge will not exceed its allowable values determined by the design standards.

When a new structure is designed the internal strains are calculated based on the estimated internal forces in the component. In order to identify the internal forces, external loads are estimated by the standards and the behaviour of the structure is anticipated. Although many efforts will be made to assure that the values are reliably and cost effectively estimated, still many assumptions in regards to the external loads, characteristics of the materials, and behaviour of the structure are required to be made.

In regards with existing structures, if the above strategy is taken to evaluate their current condition, the results will be even more uncertain as many more assumptions related to the new current condition of the structure are required to be made. The new condition of an existing structure has changed over time as the condition of many parts of it has deteriorated by aging due to environmental effects and applied external loads to the structure. Therefore, considering the considerable developments achieved in the area of measuring the responses of the structures through new technologies, for existing bridges it would be more reliable to directly measure the strains and deflections in the critical locations of the component to identify whether the component can carry its load and also whether it is serviceable.

The measurements directly show the strains of different critical locations of a component and the maximum deflections of the component, therefore, the responses do not need to be indirectly calculated though structural analysis and estimating the bending, shear, axial, and torsional forces. Through directly measuring the strains and deflections of the critical locations of a component, information about its section properties or defects in the component will not be needed, as all of them will be reflected in the measured strains and deflections. This will not only eliminate all the uncertainties in many assumptions that should be made when the structural analysis is used, but also it will make the method much easier to be implemented and make it less costly and more reliable. As the measurements are continual and are associated with the real loads which are applied to the structure; hence, the results would be highly reliable.

Based on the above discussion, in this paper the maximum capacity of a component at safely level and for all the forces mentioned before except seismic loads is defined to be the yielding strain at its critical locations. For seismic forces where the plastic capacity of the components based on the performance based methods are considered, values larger than yielding strain can be taken into account. At serviceability level according to this method, the maximum deflection defined by the standards can be considered as the maximum serviceability capacity of a component.

In order to monitor the behaviour of each component of a bridge in a network of bridges, Eqs. (1)-(10) are proposed in this paper. At a network level many bridges and components with different types of materials and structures exist, as a result, the measurements in this method are limited to strains and deflections. Eqs. (1)-(5) respectively indicate the demand by capacity ratios (DCRs) (or criticality) of component *i* of a bridge to live, flood, wind, earthquake and collision loads. Eqs. (1)-(5) also show the ratings of the component *i* in a network of bridges associated with the above mentioned different loads. They are related to safely level, and applied to steel components. Similar concept can be applied to components with other types of materials such as reinforced concrete.

$$CCAL_i = \frac{\varepsilon al_i}{\varepsilon_y} \tag{1}$$

$$CCAFL_i = \frac{\varepsilon afl_i}{\varepsilon_y} \tag{2}$$

$$CCAW_i = \frac{\varepsilon aw_i}{\varepsilon_y} \tag{3}$$

$$CCAE_i = \frac{\varepsilon ae_i}{\varepsilon_y} \tag{4}$$

$$CCCOL_i = \frac{\varepsilon acol_i}{\varepsilon_y} \tag{5}$$

where;

$CCAL_i$: Criticality and rating of component *i* associated with live load (safety level)

$CCAFL_i$, $CCAW_i$, $CCAE_i$, and $CCCOL_i$ Vulnerability and rating of component *i* in a network respectively associated with flood, wind, earthquake, and collision (safety level)

εy: Yielding strain of components

$\varepsilon al_i, \varepsilon afl_i, \varepsilon aw_i, \varepsilon ae_i, \varepsilon acol_i$: Measured strains at critical locations of component *i* respectively associated with live, flood, wind, earthquake and collision loads (safety level)

At serviceability level, as shown in Eqs. (6)-(10), in order to calculate the DCRs (or vulnerability) of component *i* related to the serviceability of the component and associated with each load (e.g., live, flood, wind, earthquake, and collision loads), the measured deflections should be divided by the maximum allowable deflections determined by design standards.

$$SAL_i = \frac{\Delta al_i}{\Delta_{allowable}} \tag{6}$$

$$SAFL_i = \frac{\Delta afl_i}{\Delta_{allowable}} \tag{7}$$

$$SAW_i = \frac{\Delta aw_i}{\Delta_{allowable}} \tag{8}$$

$$SAE_i = \frac{\Delta ae_i}{\Delta_{allowable}} \tag{9}$$

$$SCOL_i = \frac{\Delta acol_i}{\Delta_{allowable}} \tag{10}$$

where;

SAL_i: Criticality and rating of component *i* associated with live load (serviceability level)

$SAFL_i$, SAW_i, SAE_i, and $SCOL_i$: Vulnerability and rating of component *i* in a network respectively associated with flood, wind, earthquake, and collision (under serviceability loads)

$\Delta allowable$: The allowable deflections of a component determined by design standards

$\Delta al_i, \Delta afl_i, \Delta aw_i, \Delta ae_i, \Delta acol_i$: Measured deflections at critical locations of the component *i* respectively associated with live, flood, wind, earthquake and collision loads (under serviceability loads)

The strains and deflections are related to the critical locations of each important component of a bridge. The important components of a structure are those, which the load carrying capacity of the bridge is highly dependent on them. The critical locations of a component are those where the highest responses in respect to other parts of the component can be seen, when the component is subjected to different loads. For example, the critical location in respect to bending in Fig. 1 is in the middle of the beam. The critical locations of the component and the important components of a bridge could be identified though structural analysis and considering the capacity of the components as explained in synthetic rating method and SRP. Fig. 2 shows the algorithm of the method related to live loads at safety level. For live loads at serviceability level, and for other loads at both safety and serviceability levels similar algorithm could be developed. The term live loads here refer to moving loads with different speeds, magnitudes and axle configurations (e.g., stiffness and damping systems).

By using the proposed method in this paper in synthetic rating method and SRP, the condition of the components of all bridges at a network level are monitored and those with worst conditions will be identified.

$$DCR_{(Safety)} = \frac{\varepsilon}{\varepsilon_y}$$

(a) Safety level

$$DCR_{(Serviceability)} = \frac{\Delta}{\Delta_{allowable}}$$

(b) Serviceability level

Fig. 1 DCRs of a simply-supported component at safety and serviceability levels

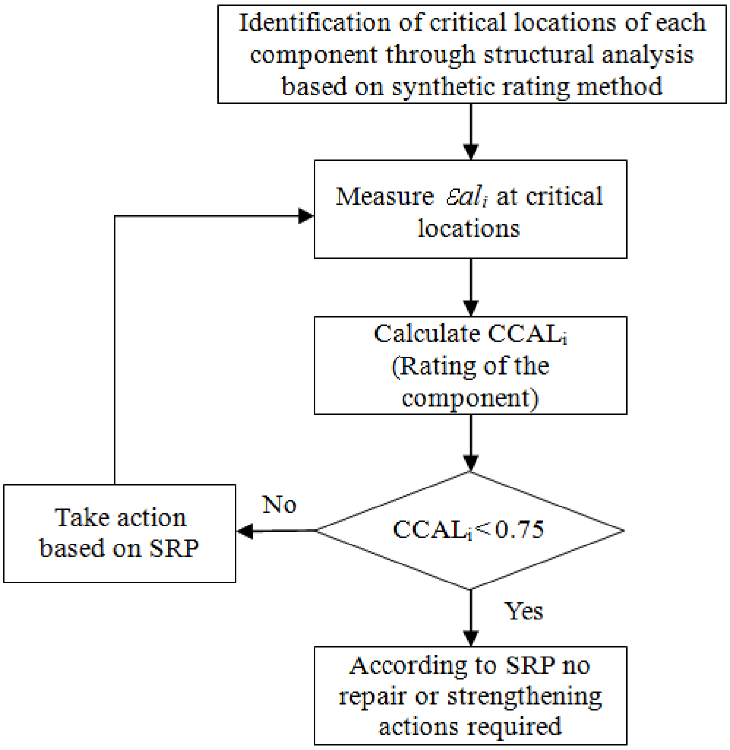

Fig. 2 Layout of the method for component i associated with live loads at safety level

Although this method provides continual information about the components of bridges, as explained in synthetic rating method structural analysis would still need to be performed to evaluate the behaviour of bridges and find the critical locations of the components. According to SRP, after narrowing down all the components in a network to those with worst condition, the detailed structural assessments including detailed structural analysis can be conducted on the associated selected bridges. The detailed structural evaluations on selected bridges can be carried out as the number of bridges under assessments is reduced from a network to a few bridges. In addition, at bridge level and for selected bridges based on the above method, in case it is required the SHM systems such as those introduced in the introduction of this paper which take into account different parameters of the structure such as natural frequencies, and modal parameters and their derivatives can be adopted for damage detection and identification.

3. Example

The following artificial example helps to illustrate the method. Ten important components of the corresponding 10 hypothetical bridges are shown in Table 1. In the third column of Table 1 as a safely margin, 60% of yielding strain was considered. The bridges were assumed to be subjected to different vehicular live loads e.g., vehicle loads with different speeds and magnitudes and axle configurations that a real bridge may experience over a period of one year. The maximum strains and deflections of the components associated with the loads were measured using an installed SHM system and compared to the corresponding allowable values. Other loads such as earthquake and flood longer period may be considered. They are not discussed in this paper; however, the procedures are similar to this example. Fig. 3 shows the $DCAL_i$ values of element E4 under different vehicle loads over a period of one year. Element E4 is related to bridge 4. Bridge 4 is subjected to one arbitrary vehicle load each day.

As mentioned before, in Eqs. (1)-(10), the $CCAL_i$, $CCAFL_i$, $CCAW_i$, $CCAE_i$, $CCCOL_i$, SAL_i, $SAFL_i$, SAW_i, SAE_i, and $SCOL_i$ values are in fact the demand by capacity ratios (DCRs) of the component *i* of a bridge at safety and serviceability levels and associated with different loads. DCR is used in synthetic rating method to calculate weighting factors. The measured responses are reflecting the condition of the component at the time of measurement and as explained before they reflect the real condition of the deteriorated components. Therefore, the rating and criticality and vulnerability of the components will be determined based on the real deteriorated condition of components and the bridge.

Table 1 Maximum strains and deflections and the corresponding $CCAL_i$ and SAL_i values

Element	εal_i	εy	Δal_i (mm)	$\Delta allowable$ (mm)	$CCAL_i$	SAL_i
E1	6.5E-04	1.14E-03	11	14	0.57	0.79
E2	7.2E-04	1.14E-03	15	17	0.63	0.88
E3	5.5E-04	1.14E-03	19	28	0.48	0.68
E4	1.01E-03	1.14E-03	35	28	0.89	1.25
E5	8.2E-04	1.14E-03	23	22	0.72	1.05
E6	9.0E-04	1.14E-03	22	19	0.79	1.16
E7	4.9E-04	1.14E-03	14	22	0.43	0.64
E8	5.6E-04	1.14E-03	18	25	0.49	0.72
E9	6.9E-04	1.14E-03	21	25	0.61	0.84
E10	5.0E-04	1.14E-03	7	11	0.44	0.64

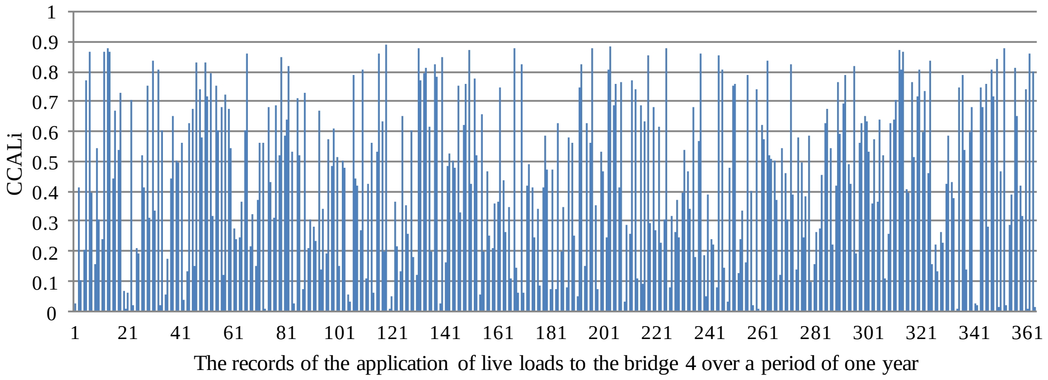

Fig. 3 Demand by capacity ratios of element E4 (CCALi) for a period of one year

Table 1 and Fig. 3 show how the behaviour of the components of a network of bridges can be monitored to obtain their maximum strains, and deflections. Subsequently, the associated demand by capacity ratios will be calculated using the Eqs. 1 and 6. As shown in Table 1, the CCALi value of the element E4 is 0.89 that means the bending moments associated with some particular vehicle loads reach to 89% of its bending capacity. The deflections associated with those loadings as shown in Table 1 is higher than allowable values. Fig. 3 provides continuous data about the magnitude and cycles of loadings, hence it will be useful for fatigue effects on the component over a long run. For each component in a network figures similar to Fig. 3 could be recorded for a long time (e.g., years). Therefore, any increase in the demand by capacity ratio of the component can indicate the increase in load or degradation of the component over years. Tables and figures similar to Table 1 and Fig. 3 can be provided for other loads as well. These tables and figures will be used in synthetic rating method and SRP (Aflatooni 2015) to continually monitor the load carrying capacities of the components under the applied loads and identify those which do not meet the safety and/or serviceability requirements.

The DCRs of the components provide an appropriate understanding on the real performance of bridges. The larger DCR values at safety and serviceability levels show the higher risk of failure of a bridge component at each safety or serviceability levels. The DCR values larger than unity show that the component cannot safely carry their loads or it cannot satisfy the serviceability requirements of the design standards.

The strains and vertical deflections can be measured by different tools and methods as briefly explained in the introduction. Each tool or method of measuring or calculating the strains or vertical deflections has its own limits, therefore, depending on the type of structure, type of component, importance of the component, atmospheric and weather condition, etc., a suitable one should be selected. A combination of them can also be used to improve the accuracy of the results.

The measured strains and deflections of all the critical components of each bridge in a network can be collected at the location of the bridge. The measured responses will then automatically be compared with the recorded yielding strains and maximum allowable deflections as can be seen in Eqs. (1)-(10), to determine the ratings or criticality and vulnerability of the components (e.g., $CCAL_i$,

$CCAFL_i$, $CCAW_i$, $CCAE_i$, $CCCOL_i$, SAL_i, $SAFL_i$, SAW_i, SAE_i, and $SCOL_i$) of the bridge. In order to identify the ratings of the condition of a component associated with each load in a network of bridges, the results will be transmitted to one place (e.g., uploaded to a network) to be compared with other similar data related to other bridges in the network.

According to SRP, when structural analysis is used, the DCRs of the bridge components are calculated and considered as weighting factors. The weighting factors of component *i* related to live, flood, wind, earthquake, and collision loads are respectively shown by parameters; al_i, afl_i, aw_i, ae_i, *and* $acol_i$ (as shown in Eqs. (A1) and (A2)). Then the $CCAL_i$, $CCAFL_i$, $CCAW_i$, $CCAE_i$, and $CCCOL_i$ values are calculated based on multiplying the current condition of the components (e.g., C_{ci}) to the preceding weighting factors (respectively e.g. $C_{ci}al_i$, $C_{ci}afl_i$, $C_{ci}aw_i$, $C_{ci}ae_i$, and $C_{ci}acol_i$ as shown in Eqs. (A1) and (A2) in Appendix). The values of C_{ci} are determined through inspection. By using the method proposed in this paper however, the criticality and vulnerability of components at safety and serviceability levels e.g., $CCAL_i$, $CCAFL_i$, $CCAW_i$, $CCAE_i$, $CCCOL_i$, SAL_i, $SAFL_i$, SAW_i, SAE_i, and $SCOL_i$ are directly the DCRs.

As by measuring the responses by using SHM systems instead of calculating them through structural analysis, the current condition of the components of bridges are continually assessed through their responses, therefore, C_{ci} which is the current condition of the component *i* is not required to be estimated through inspection and incorporated in the SRP equations. This will improve the reliability of the outcomes, as the uncertainties from inspection will not be entered in the equations of this paper. By using SHM systems the condition assessment is continual as measurements are continuously performed, contrary to identifying the criticality and vulnerability of components based on structural analysis and inspection outcomes which the results are not continual as they are updated at the time of inspections. The method proposed in this paper provide additional continual information to be used in synthetic rating method and SRP, therefore, structural analysis as explained in SRP would still need to be conducted to find the critical locations of the components and interpret the behaviour of the structure and predict the future condition of bridges.

The structural analysis based on SRP's method is used to obtain the weighting factors and criticality and vulnerability of the components (as shown in the Appendix). Recording and analysing data obtained from this method such as Fig. 3 for a longer time (say 5 years) can also help to predict the future condition of a component. In the process of conducting structural analysis, the maximum loads which the structure may be subjected to within its lifetime are predicted by the design standards, therefore, the future behaviour of the structure can be evaluated through structural analysis. This proposed method however, continually monitors the condition of each bridge component and provides reliable data about the behaviour of bridges in the network at the time of the application of each previously mentioned loads.

4. Conclusions

To summarize as elaborated in this paper, continually evaluating the safety and serviceability of bridges at a network and conducting timely maintenance and repair is an essential task in a bridge management system. Especially considering that the bridges are constantly under different types of loads and their condition is degrading due to different environmental factors. The authors of this paper have already developed the synthetic rating method and its procedures (SRP) for evaluating the current and future condition of bridges at the network level. One of the main parts of that method is calculating the criticality and vulnerability of the bridge components in a network through conducting structural analysis and calculating their demand by capacity Ratios (DCRs). This paper explains how a SHM system can be used to continually calculate the demand by capacity ratios of the bridges' components and evaluate their criticality and vulnerability. This method will be used within synthetic rating method and SRP for condition assessment and rating of bridge components.

According to this method strain gauges are used to measure the demand in components subjected to different loads including vehicle load and the loads associated with the extreme events such as flood, wind, earthquake and collision. The location of the strain gauges can be determined through performing structural analysis. The demand by capacity ratios of a component subject to different loads will then be calculated through dividing the demands which are the strains in critical locations by the yielding strains at those locations. The ratios show the criticality of the condition of a component when it is subjected to different loads. In order to evaluate the serviceability of the component of the bridge, the maximum deflections of the components or spans of a bridge is measured and it will be compared with the maximum deflection limits identified by design standards. The ratios of measured deflections with maximum deflections identified by standards show the serviceability of the component or a bridge at a network level. The above ratios both at safety and serviceability levels are used to continually determine the ratings of a component in a network of bridges and their components.

The proposed method will focus on the behaviour of the structure at the time of the application of forces. In order to be able to interpret the behaviour of a bridge, structural analysis would still need to be conducted as explained in SRP. As this method is based on measuring the responses of the structure, the deteriorated condition of the components at the time of measurement is taken into account. According to the method, only strain and deflection responses of components in a network of bridges are used to evaluate their criticality and vulnerability. The reason is that this method should be applied to a network of bridges; therefore, it should be simple to be applicable to a massive number of components and bridges at a network level. According to synthetic rating method for those limited bridges and their components which their condition are identified as critical, detailed structural analysis can be performed or more detailed SHM systems can be adopted to assess their condition. Continually evaluating the condition of bridges which many of them are old and heavily loaded through the SRP and the proposed method in this research, helps to prevent sudden collapses of structures and maintain the serviceability of bridges at a network level.

Acknowledgments

The authors are grateful to the CRC for Rail Innovation (established and supported under the Australian Government's Cooperative Research Centres program) for the funding of this research. Project No. R3.118 and Project Title: Life Cycle Management of Railway Bridges.

References

Abdalla, M., Grigoriadis, K. and Zimmerman, D. (2000), "Structural damage detection using linear matrix inequality methods", *J. Vib. Acoust.*, **122**(4), 448-455.

Aflatooni, M. (2015), *Synthetic Rating System for Railway Bridge Management*, PhD Thesis, Queensland

University of Technology.

Aflatooni, M., Chan, T.H.T. and Thambiratnam, D.P. (2014), “Synthetic rating procedures for rating railway bridges”, *J. Bridge Eng*., **19**(12), doi: 10.1061/(ASCE)BE.1943-5592.0000623

Aflatooni, M., Chan, T.H.T. and Thambiratnam, D.P. (2015), “A new look at the restrictions on the speed and magnitude of train loads for bridge management”, *Struct. Eng. Mech*., **53**(1), 89-104.

Bandara, A.R.P. (2013), Damage identification and condition assessment of building structures using frequency response functions and neural networks.

Bandara, R.P., Chan, T.H. and Thambiratnam, D.P. (2014), “Frequency response function based damage identification using principal component analysis and pattern recognition technique”, *Eng. Struct*., **66**, 116-128.

Bao, X., DeMerchant, M., Brown, A. and Bremner, T. (2001), “Tensile and compressive strain measurement in the lab and field with the distributed Brillouin scattering sensor”, *J. Lightwave Technol*., **19**(11), 1698.

Catbas, F., Gul, M. and Burkett, J. (2008), “Damage assessment using flexibility and flexibility-based curvature for structural health monitoring”, *Smart Mater. Struct*., **17**(1), 015024.

Chan, T.H., Ashebo, D.B., Tam, H., Yu, Y., Chan, T., Lee, P. and Gracia, E.P. (2009), “Vertical displacement measurements for bridges using optical fiber sensors and CCD cameras—a preliminary study”, *Struct. Health Monit*., **8**(3), 243-249.

Chan, T.H. and Wang, Y. (2013), “Australian network of structural health monitoring”, *Australian J. Struct. Eng*., **14**(1).

Chan, T.H., Yu, L., Tam, H.Y., Ni, Y.Q., Liu, S., Chung, W. and Cheng, L. (2006), “Fiber bragg grating sensors for structural health monitoring of Tsing Ma bridge: Background and experimental observation”, *Eng. Struct*., **28**(5), 648-659.

Chan, T.H.T. and Thambiratnam, D.P. (2011), *Structural Health Monitoring in Australia*. Brisbane, Australia: Nova Science Publishers, Hauppauge NY.

Chan, T.H.T., Wong, K., Li, Z. and Ni, Y.Q. (2011), *Structural health monitoring for long span bridges: Hong Kong experience & continuing onto Australia, Chapter 1 in Structural Health Monitoring in Australia, edited by Chan, T.H.T and Thambiratnam, D.P.*: NOVA Science Publishers, Inc.

Hassiotis, S. (2000), “Identification of damage using natural frequencies and Markov parameters”, *Comput. Struct*., **74**(3), 365-373.

Henault, J.M., Quiertant, M., Delepine-Lesoille, S., Salin, J., Moreau, G., Taillade, F. and Benzarti, K. (2012), “Quantitative strain measurement and crack detection in RC structures using a truly distributed fiber optic sensing system”, *Constr. Build. Mater*., **37**, 916-923.

Jáuregui, D.V., White, K.R., Woodward, C.B. and Leitch, K.R. (2003), “Noncontact photogrammetric measurement of vertical bridge deflection”, *J. Bridge Eng*., **8**(4), 212-222.

Ko, J. and Ni, Y. (2005), “Technology developments in structural health monitoring of large-scale bridges”, *Eng. Structu*., **27**(12), 1715-1725.

Lee, J.J., Lee, J.W., Yi, J.H., Yun, C.B. and Jung, H.Y. (2005), “Neural networks-based damage detection for bridges considering errors in baseline finite element models”, *J. Sound Vib*., **280**(3), 555-578.

Li, Z., Chan, T.H. and Zheng, R. (2003), “Statistical analysis of online strain response and its application in fatigue assessment of a long-span steel bridge”, *Eng. Struct*., **25**(14), 1731-1741.

Li, Z. and Chan, T.H.T. (2006), “Fatigue criteria for integrity assessment of long-span steel bridge with health monitoring”, *Theor. Appl. Fract. Mech.*, **46**(2), 114-127.

Li, Z., Chan, T.H.T., Yu, Y. and Sun, Z. (2009), “Concurrent multi-scale modeling of civil infrastructures for analyses on structural deterioration--Part I: Modeling methodology and strategy”, *Finite Elem. Anal. Des*., **45**(11), 782-794.

Liang, M.T., Wu, J.H. and Liang, C.H. (2001), “Multiple layer fuzzy evaluation for existing reinforced concrete bridges”, *J. Infrastruct. Syst*., **7**(4), 144.

Micro measurements a VPG Brand. (2014), Strain Gauge Selection: Criteria, Procedures, Recommendations Retrieved 19/11/2014, 2014, from http://www.vishaypg.com/docs/11055/tn505.pdf

Nobahari, M. and Seyedpoor, S. (2011), “Structural damage detection using an efficient correlation-based index and a modified genetic algorithm”, *Math. Comput. Modell*., **53**(9), 1798-1809.

Ogundipe, O., Roberts, G.W. and Brown, C.J. (2014), “GPS monitoring of a steel box girder viaduct”, *Struct. Infrastruct. E.*, **10**(1), 25-40.

Park, H., Lee, H., Adeli, H. and Lee, I. (2007), “A new approach for health monitoring of structures: terrestrial laser scanning”, *Comput.-Aided Civil Infrastruct. E.*, **22**(1), 19-30.

Radzieński, M., Krawczuk, M. and Palacz, M. (2011), “Improvement of damage detection methods based on experimental modal parameters”, *Mech. Syst. Signal Pr.*, **25**(6), 2169-2190.

Reynders, E., Teughels, A. and De Roeck, G. (2010), “Finite element model updating and structural damage identification using OMAX data”, *Mech. Syst. Signal Pr.*, **24**(5), 1306-1323.

Roy, K. and Ray-Chaudhuri, S. (2013), “Fundamental mode shape and its derivatives in structural damage localization”, *J. Sound Vib.*, **332**(21), 5584-5593.

Salawu, O. (1997), “Detection of structural damage through changes in frequency: a review”, *Eng. Struct.*, **19**(9), 718-723.

Sampaio, R., Maia, N. and Silva, J. (1999), “Damage detection using the frequency-response-function curvature method”, *J. Sound Vib.*, **226**(5), 1029-1042.

Shih, H.W., Thambiratnam, D.P. and Chan, T.H. (2009), “Vibration based structural damage detection in flexural members using multi-criteria approach”, *J. Sound Vib.*, **323**(3), 645-661.

Sohn, H. (2004), *A review of structural health monitoring literature: 1996-2001*: Los Alamos National Laboratory.

Taha, M.R., Noureldin, A., Lucero, J. and Baca, T. (2006), “Wavelet transform for structural health monitoring: a compendium of uses and features”, *Struct. Health Monit.*, **5**(3), 267-295.

Vurpillot, S., Inaudi, D. and Scano, A. (1996), *Mathematical model for the determination of the vertical displacement from internal horizontal measurements of a bridge*, Paper presented at the 1996 Symposium on Smart Structures and Materials.

Wang, F., Chan, T., Thambiratnam, D. and Tan, A.C. (2013), “A statistical strategy to select optimal structural health monitoring data in operational modal analysis”, *Australian J. Struct. Eng.*, **14**(1), 1-12.

Wang, L. (2012), *Innovative damage assessment of steel truss bridges using modal strain energy correlation*, PhD Thesis, Queensland University of Technology.

Wu, J. and Li, Q. (2006), “Structural parameter identification and damage detection for a steel structure using a two-stage finite element model updating method”, *J. Constr. Steel Res.*, **62**(3), 231-239.

Yang, J.N. and Lin, S. (2005), “Identification of parametric variations of structures based on least squares estimation and adaptive tracking technique”, *J. Eng. Mech. -ASCE*, **131**(3), 290-298.

Yau, M.H. (2014), Vertical displacement measurement using fibre Bragg grating (FBG) sensors for structural health monitoring of bridges.

Yau, M.H., Chan, T.H., Thambiratnam, D. and Tam, H. (2013), “Static vertical displacement measurement of bridges using fiber Bragg grating (FBG) sensors”, *Adv. Struct. Eng.*, **16**(1), 165-176.

Zhou, Y.E. (2006), “Assessment of bridge remaining fatigue life through field strain measurement”, *J. Bridge Eng.*, **11**(6), 737-744.