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Rating System for Bridge Condition Assessment

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Road infrastructure in our country is increasing rapidly. Bridges are used to connect the road networks to cross obstacles like a river, railway crossings or grade separators. Bridges are now an integral part of the urban transport system where elevated roads and metro lines are constructed for efficient traffic management. Monitoring of the bridge is essential as the bridge failure may be catastrophic causing the death of human beings and loss of the national economy. Assessment of bridge condition in terms of condition rating gives a unique rating value that can be directly related to the condition of the bridge. Moreover, these rating values can also be used to develop the deterioration model of the bridge which can be useful for inspection engineers to prepare effective repair and rehabilitation strategies. The inspection data for bridge condition assessment may also be useful to identify the problems related to a design by analyzing the type of failure in the bridge. Further, these data can be used to investigate the deterioration phenomena which will use to avoid sudden failure of the bridges. In India, still, proper bridge condition assessment techniques have not been developed due to lack of inventory and inspection data. Conventional techniques of condition assessment are mostly based on visual inspection supplemented with some non-destructive evaluation techniques which are not capable of damage detection at a very early stage. To develop a rating system for the bridge, those parameters are identified which are sensitive to the damage in the bridge. In this paper, parameters of the existing bridge management system of different countries have been reviewed and some additional parameters have been recommended that are sensitive to incipient level damage.

KEYWORDS

Bridge condition assessment, Structural health monitoring, Bridge condition rating

1. INTRODUCTION

The socio-economic growth of any nation is directly related to the growth of transport infrastructure. Bridges are considered the most vulnerable structure among the transport infrastructure whose failure may be catastrophic causing economic diminution and loss of human life [1-3]. Expeditious growth in the construction of bridges has been witnessed in the last few decades in India. The condition of bridges is degrading with increased loading, vehicle movement and deterioration of the material due to aggressive environmental factors [4]. To maintain a minimum level of service, there must be an inspection to check the level of deterioration and preventive measures should be taken to mitigate the deterioration of the bridge [5]. Condition assessment is the technique in which the present condition of the existing structure is evaluated by measuring the different state parameters. This process generally involves identification of the parameters, diagnosis of the damage, localization and quantification of damage and assessment of the present condition [1]. Conservative assessment of the bridge will result in superfluous actions, such as costly repair and rehabilitation and delayed bridge maintenance actions may lead to heavy future maintenance costs or deteriorated assets [6]. The current practice of bridge condition assessment is mostly based on visual inspection by experts which requires physical inspection at regular intervals [1,7-9]. Condition assessment based on visual inspection is very subjective and often gives conservative results. Many secondary factors are either not considered or very difficult to evaluate [9]. Some advanced non-destructive evaluation (NDE) techniques, like acoustic emission (AE), ultrasonic pulse velocity (UPV), impact echo (IE); electrical methods, like infrared thermography (IR); electromagnetic methods, like ground-penetrating radar (GPR) and rebound hammer can quantify damage upto certain extent [1,7,10]. Olson used impact echo scanning (IES) for the detection of poorly grouted/voided ducts and in the bridge deck scanner (BDS-IE) for delamination [11]. Integration of two or more NDE methods can improve the reliability of the result [12]. One major drawback to these methods is that they interrogate structure at the local level which makes them less reliable for global condi-

Table 2. *Proposed rating system for the bridges*

Rating value	Condition	Assessment criteria
10	Excellent condition	(a) Equivalent stiffness change is up to 1% for all components
		(b) Frequency change is up to 0.01%
		(c) No damage/ crack was observed by visual inspection
9	Very good condition	(a) Equivalent stiffness change is up to 2% for all components
		(b) Frequency change is up to 0.01%
		(c) No damage/ crack was observed by visual inspection
8	Good condition	(a) Equivalent stiffness change is up to 5% for all components
		(b) Frequency change is up to 0.01%
		(c) No damage/ crack was observed by visual inspection
7	Satisfactory	(a) Equivalent stiffness change is up to 10% for all components
		(b) Frequency change is up to 0.1%
		(c) No damage/ crack was observed by visual inspection
6	Fair condition	(a) Equivalent stiffness change is up to 15% for all components
		(b) Frequency change is up to 0.1%
		(c) Damage/cracks were observed by visual inspection in non-structural elements only
5	Poor condition	(a) Equivalent stiffness change is up to 30% for all components
		(b) Frequency change is up to 2.0%
		(c) Damage/cracks were observed by visual inspection in the superstructure
4	Serious condition	(a) Equivalent stiffness change is up to 50% for all components
		(b) Frequency change is up to 5%
		(c) Damage/cracks were observed by visual inspection in all components of the bridge
3	Critical condition	(a) Equivalent stiffness change is more than 50% for all components
		(b) Frequency change is more than 5%
		(c) Damage/cracks were observed by visual inspection in all components of the bridge
2	Imminent failure condition	(a) Equivalent stiffness change is more than 50% for all components
		(b) Frequency change is more than 20%
		(c) Severe damage/cracks were observed by visual inspection in all components of the bridge
1	Failed condition	(a) Equivalent stiffness change is more than 50% for all components
		(b) Frequency change is more than 50%
		(c) Severe damage/cracks were observed by visual inspection in all components of the bridge

tion assessment [1]. Dynamic parameters like bridge natural frequency, mode shape and damping ratio can be the basis for the assessment of damage location and severity. The damage index based on the dynamic response of the structure can be used for the assessment of single and multiple damages [13,14]. Various damage indices have been proposed including strain mode shape, flexibility matrix, mode shape curvature and modal strain energy; these methods mainly use structural acceleration and strain dynamic responses [15-19]. To deal with uncertain information, many tools such as fuzzy numbers of fuzzy set theory, belief function of Dempster-Shafer theory and D numbers have been used [20-22]. Yusuf used an artificial neural network (ANN) and multiple regression analysis (MRA) to model bridge condition ratings based on a limited number of data sets [23]. Another technique of condition assessment is to provide a rating value to the structure based on present structural evaluation on a predefined scale known as bridge condition rating. In the present study, the parameters used for bridge condition rating are reviewed and the existing rating system has been modified by incorporating two new parameters.

2. MATERIAL AND METHOD

2.1 Bridge condition rating

Condition assessment in terms of rating index improves the decision support system of the bridge management system (BMS) in maintenance repair and rehabilitation (MR and R). The current practice of condition rating is based mostly on routine visual inspection which is generally done once in two years. BMS of different countries have developed their system of condition rating which depends on the type of inspection, evaluation criteria and rating scale [4].

2.1.1 Comparison of existing BMS: A summary of the rating system of different countries has been given in table 1. These rating systems are mostly based on visual inspection supplemented with some local non-destructive evaluation (NDE) techniques. Rating obtained through visual inspection of components are very subjective. Moreover, these rating systems indicate the severity and extent of deterioration at a stage when the deterioration is visible through the naked eye [24]. Most of these rating systems are developed using parameters, like cracks, corrosion, delamination, spalling, loss of section, etc., through visual inspection. One major limitation of these rating systems is that it does not indicate the deterioration in structure in the very early stage. Early detection of damage can help bridge inspectors in maintenance repair and rehabilitation (MR and R) activities. The importance of visual inspection can not be neglected as it helps in identifying localized damage very easily.

2.1.2 Dynamic parameters for condition rating: Dynamic properties of structures, like natural frequencies, mode shapes, modal damping ratios, modal strain energy, mode shape curvature and others can detect the change in the condition of the structures (mass, stiffness and damping) [25]. Vibration-based SHM systems are capable to measure these parameters with the help of sensors. Extensive work has been carried out in this field and many damage-detection algorithms have been developed. Much literature has been found that shows the correlation of these dynamic parameters with damage detection. Natural frequency has been used promptly as dynamic parameter to detect damage at the global level [26-27]. Several researchers used frequency response function (FRP) for detecting damage in the bridge [28-32]. Many damage detection algorithm has been developed using mode shapes or their derivatives, like the damage index (DI) method, mode shape curvature (MSC) method, modal flexibility index (MFI) [28,33-34]. Cerda experimented with a laboratory scale model in which they varied the location and size of artificial damage and determined the location and severity of damage using multi-class classification with several discrete classes [35]. Niu used a modal strain energy-based damage index to detect damage within the girders [36]. Slater proposed a method to detect damage in smart structure using frequency shift measurement [37]. Meneghetti presented a formulation for locating a crack in a beam using natural frequency [38]. Farrar and Tang observed in their investigation that mode shapes are a better indicator of damage than natural frequencies [39,40].

Several parameters are used to prepare the rating scale. However, these parameters must be sensitive to the health of the bridge. Most of the parameters used for the present rating system are not related to the health of the bridges directly, consequently do not give reliable results on the rating scale. However, the health of the bridges depends upon the presence of damages in the different components of the bridges. Different types of damage were present in the bridges and can be classified as incipient, moderate, severe and very severe damage. Once, the damages are initiated in the components of the bridges, their severity is increased with time and incipient damage is converted into moderate and finally, converted to severe. Finally, the bridge failed within a very less duration. Hence, more weightage must be provided to the presence of incipient level damage in the structure. If the incipient damages in the bridge are determined at the time of initiation and the rating of the bridge is modified due to the induced damages, appropriate retrofitting can be applied to the bridge so that further propagation of the damages can be arrested. Apart from this, once the damage is initiated in the bridge, it will propagate very fast and the condition of the bridge will deteriorate rapidly. It is justified to give more weightage to the presence of incipient damages in the bridges for the rating scale.

It is difficult to determine the incipient level of damage in the bridge. There are various non-destructive methods to determine the presence of damage in the bridges which are described in section 1. However, incipient damage cannot be determined by these traditional non-destructive methods. PZT-based electromechanical impedance (EMI) technique can detect the incipient level damage in the structure. Moreover, in this technique, data can be extracted continuously or at regular intervals as per need.

2.2 Electromechanical impedance technique

The key element of the EMI technique is the PZT patch. The PZT patch can be bonded on the surface of the structural components or embedded inside the interrogated components of the structure. After bonding the PZT patch on the surface of the structure, it becomes an integral part of the structure. Any change in the structure is reflected by bonded PZT sensor. The response of the coupled system can be given by equation 1.

$$\overline{Y} = 4\omega j\ (l^2/h)\ [\overline{(E^T{}_{33})} - [((2d^2{}_{31}\overline{Y^E})/(1-\upsilon)) + ((2d^2{}_{31}\overline{Y^E})/(1-\upsilon))(Z_{a,eff} / Z_{s,eff} + Z_{a,eff})\ \overline{T}]] \quad ...(1)$$

Where, Y is complex electromechanical admittance, ω is angular velocity, l is half-length of PZT patch, j is under-root of -1, h is thickness of PZT patch, $(\overline{Y^E})$ is complex Young's modulus of elasticity at a constant electric field, d is piezo-electric strain coefficient, $(\overline{e^T})$ is complex electric permittivity at constant stress and Z is mechanical impedance.

The occurrence of incipient damages in any component of the bridge is reflected in terms of change in the signature. The signature of the coupled system can be obtained using the LCR meter. It contains the basic properties, like mass, damping and stiffness of the bridge as well as the PZT patch. The properties of the PZT patch can be determined before bonding on the surface of the bridge and can be filtered out from the extracted signature of the coupled system. The filtered signature contains the basic properties of bridges. Any change in the bridge in terms of damage is reflected in the signature. The signature can be decomposed in terms of conductance and susceptance. Hence, these parameters are used to predict the condition assessment and condition rating of the bridge.

Since the EMI technique works in the high-frequency range. The frequency change of the structure due to deterioration can not be determined. However, any deterioration in the bridge is reflected in terms of change in the conductance and susceptance. The equivalent stiffness of the bridge can be determined using the extracted conductance and susceptance value. The quantification of the condition assessment can be done using the equivalent stiffness. The change can be determined in terms of equivalent stiffness [41]. Hence, the equivalent stiffness can be used as a significant parameter to calculate the rating scale system. This parameter is very sensitive to incipient-level damage. Once the current equivalent stiffness is calculated and compared with the healthy state equivalent stiffness. If the appreciable change is observed in the equivalent stiffness that indicates the presence of incipient damage in the structure. The incipient damage cannot be determined using traditional methods. Hence, traditional methods fail to detect these types of damage.

3. RESULT AND DISCUSSION

3.1 Proposed rating system

Though the visual inspection techniques are not capable of detecting damages in the structures when it is at an incipient level. The existing rating system of several countries was reviewed and a new system is proposed by adding the change in the equivalent stiffness as a new parameter in the rating scale which is given in table 2. The second parameter is the change in the first frequency of the bridge as compared to the healthy state. The third parameter is the presence of cracks/damage determined from the visual inspection of the bridge. The condition of the bridges varies from worst to excellent condition. Hence, the parameter used for the rating system must work in all conditions. Bridge rating cannot be determined using a single parameter like frequency change or visual inspection. Visual inspection is not suitable for an excellent-condition bridge. However, it can be used for worse-condition bridges because damage/distress can be observed through the naked eye. Hence these parameters have been chosen for the rating system. Equivalent stiffness is used as an indicator for the bridge having a high rating to medium rating. A change in the frequency can be used for a low rating as visual inspection.

4. CONCLUSION

A new parameter has been proposed for the calculation of the rating system of the bridge. The proposed parameter can be extracted using the EMI technique. The parameter is sensitive to the presence of incipient damage in the bridge. A new rating for BMS is proposed and a better understanding can be extracted about bridge structure. The proposed system is more effective in comparison to the traditional system and can be used for retrofitting bridges. However, the new parameter can be determined using the PZT sensors hence, installation of the sensor is essential. The value of equivalent stiffness can be determined continuously or at a certain fixed interval. The proposal system is beneficial to reduce the collapse of the bridges, retrofitting and calculating the cost of maintenance. The proposed system is useful for all types of bridges.

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