Pre and Post Retrofit behaviour of an existing Railway Open web Steel Girder bridge

Sitesh Kumar Singh[1] and Nirjhar Dhang[2]

[1] Chief Engineer/Const., EC Rly, Patna and Sponsored Research Scholar, IIT, Kharagpur, India
[2] Professor, Indian Institute of Technology, Kharagpur, India

ABSTRACT: Indian Railways have total 1,38,912 bridges on various routes (Broad Gauge, Meter Gauge & Narrow Gauge). There are 35,437 bridges which are more than 100 years old. Maintenance of important and major bridges is of prime concern as any failure in such bridges causes serious traffic disruption apart from cost and time required for restoration of these bridges. In view of the above, there is a continuous need for detailed study on structural health assessment of these bridges due to corrosion, fatigue etc. so that necessary repairs or strengthening can be carried out to increase service life of the bridge. Further the suitability of existing bridges for running of high axle loads as well as high speed trains needs to be studied. In the present study, the objective is to compare the behaviour of railway open web steel girder bridge after retrofitting work.

Keeping the above objective in mind, an instrumentation study has been conducted on a 103 years old bridge, built in 1914 in Eastern Railway (the then East Indian Railway) which is one of the busiest and oldest routes of Indian Railways and has so far carried about 1267 Gross Million Tonnes of traffic. The span of this simply supported through type steel truss bridge is 4x24.40 metres. The load bearing members (stringers) have been badly corroded and as such a speed restriction of 50 kmph had been imposed on this bridge for the safety of running traffic due to distress. Therefore, the behaviour of this bridge in pre-retrofitting and post retrofitting conditions before and after changing the stringers has been studied which is of utmost importance not only from the point of view of residual life but its adequacy to cater to increased future loadings including higher speeds. From the study, it has been observed that due to distress in the load bearing members or stringers, diagonal members carry considerably more stresses. There have been considerable changes in load redistribution pattern of all the members after retrofitting.

1 INTRODUCTION AND OBJECTIVE

Indian Railways have total 1,38,912 bridges on various routes (Broad Gauge, Meter Gauge & Narrow Gauge). There are 35,437 bridges which are more than 100 years old. Amongst 17 zonal railways, Eastern Railway (the then East Indian Railway) is one of the oldest zonal railways of Indian railways in which the first train ran on 15th August, 1854.

There are 94 permanent speed restrictions (PSRs) and 124 temporary speed restrictions (TSRs) imposed on these bridges for various reasons from structural safety considerations.

Maintenance of important & major bridges is of prime concern as any failure in such bridges causes serious traffic disruption apart from cost & time required for restoration of these bridges.

In view of the above, there is a continuous need for detailed study on structural health assessment of these bridges for damage detection, corrosion, fatigue etc. so that necessary repairs or strengthening can be carried out to increase service life of the bridge. Further the suitability of existing bridges for running of high axle loads as well as high speed trains needs to be studied. In the present study, the objective is to compare the behaviour of Railway Open web steel girder bridge after retrofitting work.

Keeping the above objective in mind, an instrumentation study has been conducted on Banka Nallah Bridge (Bridge No. 209) situated between Gangpur & Barddhaman stations of Up Main & Chord lines of Howrah Barddhaman busy quadruple route at km 104/13-17 of Howrah Division (Eastern Railway) (Figure 1(a) and 1(b)). The span of this through steel truss bridge is 4x24.40 metres each simply supported on supports. From the records, it is found that this bridge was built in 1914 for the East Indian Railway (E.I.R.) by the Contractor, P. & W. Maclellan Limited, Clutha Works Glasgow (U.K.). The steel has been manufactured by 'Skinningrove-England'.

Figure 1(a). Front view of Bridge No. 209

Figure 1(b). Side view of Bridge No. 209

This bridge has served for more than 100 years in one of the busiest & oldest routes of Indian Railways. So far it has carried about 1267 Gross Million Tonnes (GMT) of traffic. The load bearing members (Stringers) have been badly corroded and as such a speed restriction of 50 kmph has been imposed on this bridge for the safety of running traffic due to distress.

The stringers have been planned for renewal. Therefore, to study the behaviour of this bridge in pre-retrofitting & post retrofitting conditions after changing the stringers is of utmost importance not only from the point of view of residual life but its adequacy to cater to increased future loadings including higher speeds. The study on this bridge can further throw light on behaviour of other old through steel truss railway bridges.

2 LITERATURE REVIEW

This study provides a review on the structural health assessment work carried out on various bridges in India and abroad with basic focus on railway bridges.

Alves et al. (2015) presented a methodology for damage detection using genetic algorithm to numerical model of a railway bridge. The test damage was introduced based on preselected numerical parameters. The response of test damage was compared with the reference damage. The methodology showed potential to detect location & quantity of damage. Boulent et al. (2007) presented a study on identification of most fatigue-critical locations of stringer to cross-girder connection of a riveted railway bridge. The finite element (FE) model was developed and analyzed under the passage of a goods train. Brencich and Gambarotta (2009) did a case study on 90 years old the Campasso riveted railway bridge to assess its residual fatigue life. Validation of theoretical model with field measurement data showed that the 3D truss was better represented as 3D frame. Caglayan et al. (2009) studied residual fatigue life of existing steel bridges in Istanbul to ascertain their fitness to be used in the proposed augmented infrastructure. Field measurements were done and analyzed for the existing train traffic. Constantine et al. (2004) presented a study on an in-service old steel railway bridge to ascertain its condition by conducting static & dynamic field measurements as well as lab tests. Validated numerical method was developed to ascertain bridge capacity. Retrofitting measures were suggested. Goel (2006) presented a study of behaviour of stringer to floor beam connection in riveted railway open web girder bridges. It was concluded that double-angle stringer-to-floor-beam connection act as shear connection and is capable of developing appreciable moments due to rotation of stringer ends. This results into high secondary bending moment at these connections.

Goulet and Smith (2013) identified unknown uncertainty dependency on a structure by comparing measured response using optimization techniques & statistical inferences. Goulet et al. (2014) quantified the effects of modelling simplifications for structural identification of bridges. They did case study on long-span, early pre-stressed segmental box girder Grand-Mere Bridge (Canada), affected by substantial long-term vertical deflections. The interpretation approach employed is based on error-domain model falsification. Hendrik et al. (2009) presented improved methodology for bridge evaluation through finite element model updating using static and dynamic measurements. The methodology was validated on new Svinesund Bridge, and revealed a necessity to use a non-linear model to assess the structural parameters more precisely. The subsequent model could replicate the measurements with better precision.

Johansson et al. (2014) carried out preliminary assessment of existing railway bridges in Sweden for high speed traffic i.e. from 200 km/h to 250 km/h. Swedish code required that the bridges be examined with dynamic simulations to avoid excessive vibrations. Dynamic models were based on analytical equations for slab-frame bridges and analysis based on probabilistic approach was done. The method gives a preliminary assessment of upgrading a bridge network. Klinger et al. (2014) have presented a case study on steel components and joints of a railway bridge over the Elbe River at Lutherstadt Wittenberg, Germany. The study was needed due to detection of 240 mm long fatigue crack through 80% of the cross section near butt weld of one of the longest hangers. It was found that wind-induced caused unexpected vibrations of the hangers which reduced their fatigue life. Additional bracings were provided to reduce wind-induced vibrations. Butt weld was also renewed. Leander and Karoumi (2010) presented a case study on cracks found in the web of the primary steel beams of a railway bridge in Sweden. Theoretical studies showed that the cracks developed mainly due to poorly designed connections of the cross beams and out-of-plane bending of the web.

Marques et al. (2014) presented analysis of dynamic and fatigue effects on old metallic railway bridge under European Research Project FALDNESS. Both numerical (FE model validation) and experimental approaches have been used to find fatigue assessment. Pasquier and Smith (2016) applied new iterative framework for structural identification for condition assessment of old bridge structures. They carried study on an existing ageing bridge in Wayne, New Jersey (US) and concluded that such a framework is able to support structural identification with measured field results jointly with engineering judgement. Pipinato et al. (2009) presented a case study on 12.4m span 90 years old decommissioned railway bridge. Riveted connections of the shear diaphragms were identified as the critical locations.

Indian Railway has permitted plying of increased axle load of goods train from 20.32 tonne to 25 tonne (for Carrying capacity + 8 tonne + 2 tonne) on some of the broad gauge (BG) routes. Dedicated Freight Corridor (DFC) is separately being built with connection to existing yards for which feasibility for allowing 32.5 tonne axle load were assessed on 5 bridges by Ramboll (2012-2014) using ELFEN and the Finite/Discrete Element (FDE) analytical techniques. The linear working stress approach required by the Indian Railway Arch Bridge Code and Ultimate Limit State (ULS) strength assessment as per British Network Rail Guidance has been used. The results of the studies are as follows:

- The ULS assessment has found the bridges to be capable of carrying the proposed 25 tonne and 32.5 tonnes axle loadings.
- The working stress assessment has found that permissible stresses in the masonry have been exceeded under the proposed 25 tonne wagon axle loading. In reality the stresses are working within sustainable limits under existing live load as the bridge is not showing signs of distress. For this the most likely reason could be simplifying assumptions made in permissible stresses given in the Indian Railways Bridge Code for masonry are intended to be used with far simpler calculations where forces, derived from force equilibrium or linear elastic analysis, are averaged over whole numbers. In these circumstances their use to limit load carrying capacity is likely to result in an overtly conservative bridge rating.

Ribeiro et al. (2012) validated the mathematical model of a bowstring-arch railway bridge based on modal parameters such as natural frequencies, mode shapes and damping coefficients. Based on enhanced frequency decomposition method, the vibration test was done to find modal parameters. A new technique based on the modal strain energy was used for the mode pairing. The mathematical model was validated based on an experimental test of the concrete and a dynamic test under railway traffic. The results showed agreement between mathematical and experimental results.

Rocha et al. (2015) have presented a case study carried out on 6x12 m simply supported span composite ballasted track bridge. Load has been taken as TGV-double high speed train. The effects of bridge & train parameters and track irregularities have taken considered for analyzing safety criteria. Probabilistic approaches like Monte Carlo & Latin Hypercube have been combined to augment effectiveness of the appraisal.

Wallin et al. (2011) investigated 2 different methods for strengthening of a through truss railway bridge in Sweden. In one of the methods, arches were added on underside of the truss and in the other, floor beams were pre-stressed to strengthen the structural system. As a result, tension in the bottom chord was changed to compression.

Xia et al. (2012) established a dynamic analysis model for a coupled high-speed train and bridge subject to collision load. A case study was carried out on 7x32 m simply supported high speed box girder Railway Bridge. They have proposed critical speed curve for running safety of a train on a bridge for crash load with varying intensities.

Xiao et al. (2015) presented multi-direction bridge model updating using static and dynamic measurement for structural health monitoring. They concluded that it is essential to update steel girder bridge's FE model in the multi-direction in order to ensure the model's precision.

From the above literature study, it is concluded that field measurements of structural parameters can be utilized for proper structural health assessment of existing bridges.

3 METHODOLOGY ADOPTED FOR FIELD MEASUREMENT

For field measurements of superstructure, the state of the art Structural Testing System (STS) manufactured by Bridge Diagnostics Inc. (BDI), USA, has been used. The sensors were fixed to the members with the help of quick hardening epoxy/adhesive e.g. Loctite etc. These sensors were connected to STS WiFi nodes through Ethernet cables. Each WiFi node accommodated four sensors. Through the antenna of WiFi Node, the signal was transmitted to the antenna of WiFi mobile base station. Then these signals were further transmitted through WiFi to the computer as shown below (Figure 2):

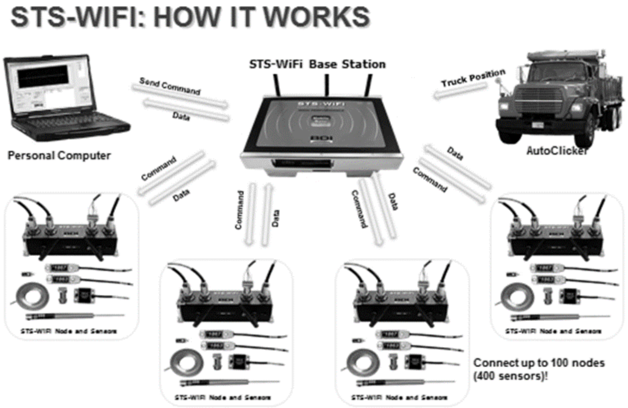

Figure 2. Working of Structural Testing System (BDI Inc., USA)

The range of Strain transducer was +/- 4000 micro-strain, sensitivity = 500 micro-strain/V_{out}/V_{ext} with accuracy < +/- 1%.

Based on theoretical analysis of the bridge using MATLAB, sensors such as strain gages, accelerometers, LVDTs, temperature gage etc. were placed at critical locations as shown in Figure 3 below:

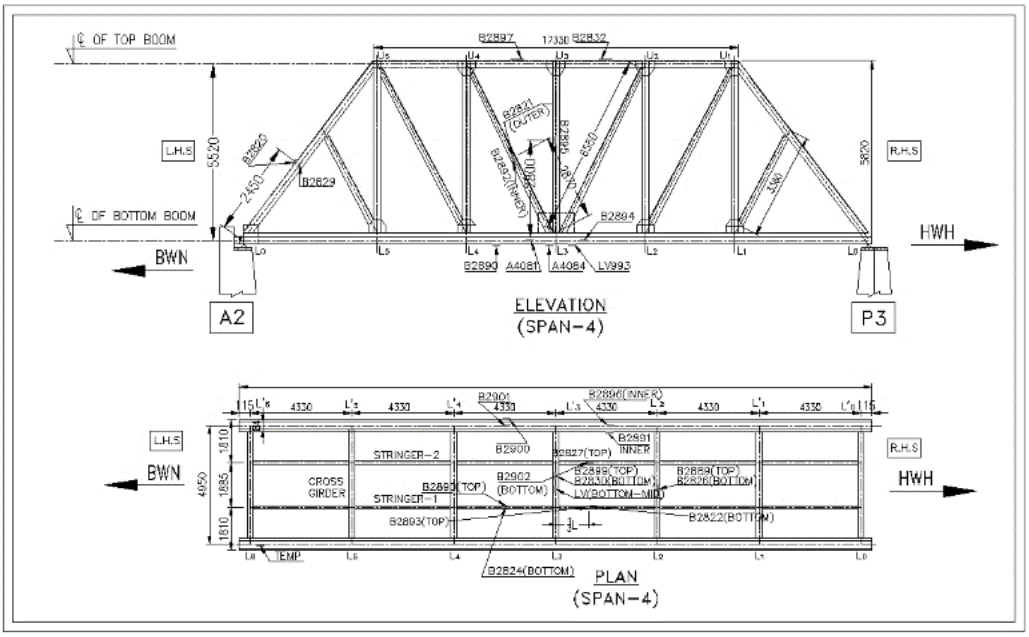

Figure 3. Location of Sensors

Pre-retrofitting measurements were taken on 3rd March, 2016 under moving load of coupled two WAG9+WAG7 locomotives (6 axles each and weighing 123 metric tonnes per loco) with 3 coal loaded BOXN wagons (weighing 75 metric tonnes each) at different speeds of 5 kmph, 15 kmph, 38 kmph & 50 kmph.

After replacement of all corroded load bearing members (stringers), post-retrofitting measurements were taken on 19th June, 2016 under moving load of coupled two WDG4+WDG4 locomotives (6 axles each and weighing 126 metric tonnes per loco) at different speeds of 5 kmph, 15 kmph & 30 kmph.

4 OBSERVATIONS

The pre and post measured values have been summarized in the following Table 1:

Table 1. Comparison of Stresses and Deflections at identical locations

Sensor Loc.	Location	Measured max avg stress (Mpa)				%age Change	
		Pre-retrofitting		Post-retrofitting		W.r.t. Pre-retrofitting	
		+ve	–ve	+ve	-ve	+ve	-ve
1	Top chord U3-U4 Flange at mid span	0.00	-41.17	0.00	-35.83	0.00	-12.97
2	Top chord U2-U3 Flange at mid span	0.00	-14.08	0.00	-14.4	0.00	-2.27
3	Diagonal member L3-U4 @2.87m from L3 on inner side	18.62	-8.68	22.91	-9.16	23.04	-5.53
4	Diagonal member L3-U4 @2.87m from L3 on outer side	12.49	-9.85	4.12	-3.14	67.01	-68.12
5	Vertical member @2.80m from L3	11.06	0.00	10.62	0.00	3.98	0.00
6	LHS End raker U5-L6 Flange @2.45m from L6	0.00	-29.38	0.00	-27.93	0.00	-4.94
7	LHS End raker U5-L6 Web @2.45m from L6	0.00	-33.90	0.00	-29.99	0.00	-11.53
8	Bottom chord Web near L3 on inner side of Outside Channel	21.61	0.00	20.87	0.00	3.42	0.00
9	Bottom chord Bottom Flange at L2 - L3 mid span Inside Channel	4.79	0.00	7.08	0.00	47.81	0.00
10	Cross Girder L3 Top at Mid span	0.00	-46.93	0.00	-33.85	0.00	-27.87
11	Cross Girder L2 Top at mid span	0.00	-40.45	0.00	-49.94	0.00	-23.46
12	Cross Girder L2 Bottom at Mid span	48.25	0.00	20.92	0.00	56.64	0.00
13	Cross Girder L3 Bottom at Mid span	17.22	0.00	21.29	0.00	23.64	0.00
14	RHS Stringer L2-L3 Bottom at 1/3rd from L3	12.19	-3.64	14.75	-2.91	21.00	-20.06
15	Vertical Deflection (mm)		8.80		7.90		
16	Lateral Deflection (mm)	6.60	5.80	5.20	5.80		

The above values have been compared graphically as shown in Figure 4.

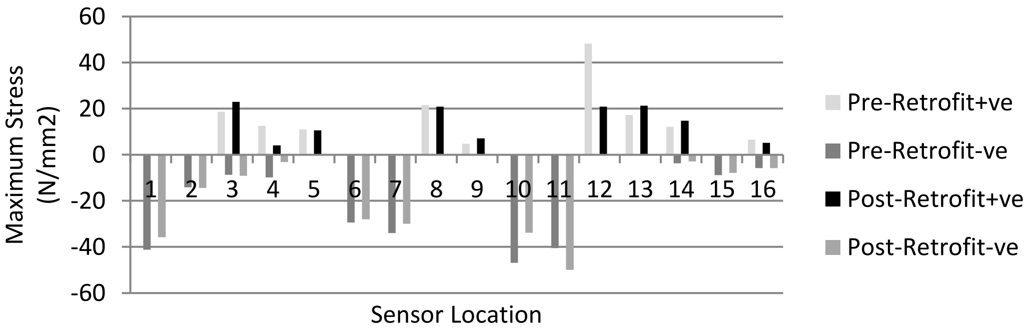

Figure 4. Comparison of Pre and Post retrofit stresses at identical locations

After replacement of corroded girders, the following important observations have been made:

1. It has been observed that compressive & tensile stresses in the diagonal member L3-L4 on outer side have reduced considerably by 68%. However, there has been 23% increase in compressive stress for this member on inner side.
2. It has been further observed that tensile stress in cross girder L2 bottom has reduced by 57% whereas there is 23% increase in compressive stress at top for this member. Tensile stress in cross girder L3 bottom has increased by 24% whereas there is 28% reduction in compressive stress at top for this member.
3. In the replaced stringer, there is 21% increase in tensile stress while 20% reduction in compressive stress.
4. In the end raker & top chord, there is 12% & 13% reduction in compressive stresses respectively.
5. In the bottom chord bottom flange, tensile stress has increased by 48%, though actual increase in the tensile stress is from 4.8 MPa to 7 MPa.

In addition, some typical observations have been also made as mentioned below:

6. Inner side of the diagonal member carries substantially more compressive and tensile stresses than the outer side of the same member.
7. End raker web carries substantially more compressive stress than the flange at the same location.
8. Stringers experience reversal of stresses.

5 CONCLUSION

From the above observations, it is concluded that:

i. Due to distress in the load bearing members or stringers, diagonal members carry considerably more stresses.
ii. In the replaced stringer, there has been increase in induced tensile stress but reduction in induced compressive stress.
iii. Since stringers and cross girders are mutually connected as part of the floor system, change in load carrying pattern in stringers affect compressive and tensile stresses induced in the cross girders as well.
iv. There has been reduction in compressive stresses in top chord and end raker members i.e. compression members.
v. In bottom chord member, i.e. tension member, there has been increase in tensile stress after retrofitting. This may be due to increase in tensile stress at bottom in stringers.
vi. In the prismatic built-up sections, stress distribution is non-uniform at flange/web at the same location.

6 REFERENCES

Alves, Vinicius., Meixedo, Andreia., Ribeiro, Diogo., Calçada, Rui., and Cury, Alexandre. (2015). “Evaluation of the Performance of Different Damage Indicators in Railway Bridges”. *Procedia Engineering*, Volume 114.

Boulent, M. Imam., Righiniotis, Timothy D., and Chryssanthopoulos, Marios K. (2007). “Numerical modelling of riveted railway bridge connections for fatigue evaluation”. *Engineering Structures*, Volume 29, Issue 11.

Brencich, Antonio., and Gambarotta, Luigi. (2009). “Assessment procedure and rehabilitation of riveted railway girders: The Campasso Bridge”. *Engineering Structures*, Volume 31, Issue 1.

Caglayan, BO. Ozakgul, K., and Tezer, O. (2009). “Fatigue life evaluation of a through-girder steel railway bridge”. *Engineering Failure Analysis*, Volume 16, Issue 3.

Constantine, C. Spyrakos, Raftoyiannis, Ioannis G., and Ermopoulos, John Ch. (2004). "Condition assessment and retrofit of a historic steel-truss railway bridge". *Journal of Constructional Steel Research*, Volume 60, Issue 8.

Goel, R.K. (2006). "Study of Behaviour of Stringer to Floor Beam connection in riveted Open Web Girder bridges". *Journal of Institution of Permanent Way Engineers (India)*.

Goulet, James A., and Smith, I. F.C. (2013). "Structural identification with systematic errors and unknown uncertainty dependencies". *Computers and Structures*, Volume 128.

Goulet, J., Texier, M., Michel, C., Smith, I., and Chouinard, L. (2014). "Quantifying the effects of modelling simplifications for Structural Identification of Bridges". *Journal of Bridge Engineering*, Volume 19, Issue 1.

Hendrik, Schlune., Mario, Plos., and Kent, Gylltoft. (2009). Improved bridge evaluation through finite element model updating using static and dynamic measurements, *Engineering Structures*, Volume 31, Issue 7

Indian Railways Bridge Manual, 1998.

Indian Railways Bridge Rules, 2014.

Johansson, C., Nuallain, N.A.Ni., Pacoste, C., and Andersson, A. (2014). "A methodology for the preliminary assessment of existing railway bridges for high-speed traffic". *Engineering Structures*, Volume 58.

Klinger, C., Michael, Th. and Bettge, D. (2014). "Fatigue cracks in railway bridge hangers due to wind induced vibrations – Failure analysis, measures and remaining service life estimation". *Engineering Failure Analysis*, Volume 43.

Leander, John., Andersson, Andreas. and Karoumi, Raid. (2010). "Monitoring and enhanced fatigue evaluation of a steel railway bridge". *Engineering Structures*, Volume 32, Issue 3.

Marques, Fernando., Moutinho, Carlos., Magalhaes, Filipe., Elsa, Caetano., and Cunha, Alvaro. (2014). "Analysis of dynamic and fatigue effects in an old metallic riveted bridge". *Journal of Constructional Steel Research*, Volume 99.

Pasquier, Romain, and Smith, Ian FC. (2016). "Iterative structural identification framework for evaluation of existing structures". "*Engineering Structures*", Volume 106.

Pipinato, A., Pellegrino, C., Bursi, O.S., and Modena, C. (2009). "High-cycle fatigue behavior of riveted connections for railway metal bridges". *Journal of Constructional Steel Research*, Volume 65, Issue 12.

Ramboll, Southampton, UK. (2012-2014). "Monitoring and assessment of Eastern Railway bridge reports".

Ribeiro, D., Calçada, R., Delgado, R., Brehm, M., and Zabel, V. (2012). "Finite element model updating of a bowstring-arch railway bridge based on experimental modal parameters". Engineering Structures, Volume 40.

Rocha J.M., Henriques, A.A., Calçada, R., and Rönnquist, A. (2015). "Efficient methodology for the probabilistic safety assessment of high-speed railway bridges". *Engineering Structures*, Volume 101.

Wallin, Joakim., Leander, John., and Karoumi, Raid. (2011). "Strengthening of a steel railway bridge and its impact on the dynamic response to passing trains". *Engineering Structures*, Volume 33, Issue 2.

Xia C.Y., Lei J.Q., Zhang N., Xia H., and Roeck G. De. (2012). "Dynamic analysis of a coupled high-speed train and bridge system subjected to collision load". *Journal of Sound and Vibration*, Volume 331, Issue 10.

Xiao, Feng., Hulsey, J. Leroy., and Chen, Gang S. (2015). "Multi-direction bridge model updating using static and dynamic measurement". *Applied Physics Research*, Vol. 7, No. 1.