THOMSON REUTERS ENDNOTE

[Tomar et al., 3(7): July, 2016] ISSN 2349-4506
Impact Factor: 2.545

Global Journal of Engineering Science and Research Management

SEISMIC VULNERABILITY ASSESSMENT OF BRIDGES USING FRAGILITY-BASED APPROACH

Ritu Tomar*, Manish Kumar Nimoriya, Shailendra Singh
* Research Scholar, Department of Civil Engineering, Malwa Institute of Science & Technology, Indore
Department of Civil Engineering, Indore Institute of Science & Technology, Indore
Department of Civil Engineering, Indore Institute of Science & Technology, Indore

DOI: 10.5281/zenodo.58272

KEYWORDS: Highway Bridge, Vulnerability, Fragility Curve, Damage Limit State.

ABSTRACT
Dynamic loads can cause severe damage to bridges, and lead to malfunction of transportation networks. A comprehensive understanding of the nature of the dynamic loads and the structural response of bridges can prevent undesired failures while keeping the cost-safety balance. Dissimilar to the static behaviour, the dynamic response of bridges depends on several structural parameters such as material properties, damping and mode shapes. Furthermore, dynamic load characteristics can significantly change the structural response. In most cases, complexity and involvement of numerous parameters require the designer to investigate the bridge response via a massive numerical study.

Depending on the seismicity of the bridge local site, seismic vulnerability assessment of the bridges can be done based on the fragility curves. These curves are conditional probability functions which give the probability of a bridge attaining or exceeding a particular damage level for an earthquake of a given intensity level. In this dissertation, analytical fragility curves are developed for the ordinary highway bridges in the assessment of their seismic vulnerability. Bridges are first grouped into certain major bridge classes based on their structural attributes and sample bridges are generated to account for the structural variability. Nonlinear response history analyses are conducted for each bridge sample with their detailed 3-D analytical models under different earthquake ground motions having varying seismic intensities. Several engineering demand parameters are employed in the determination of seismic response of the bridge components as well as defining damage limit states in terms of member capacities. Fragility curves are obtained from the probability of exceeding each specified damage limit state for each major bridge class. Skew and single-column bent bridges are found to be the most vulnerable ones in comparison with the other bridge classes. Developed fragility curves can be implemented in the seismic risk assessment packages for mitigation purposes.

INTRODUCTION
Bridges are an important part of the surface transportation system. Failure in a bridge operation can cause severe economic, environmental and/or social consequence. A considerable number of bridge failures, caused by natural or human-made forces, can be prevented by theoretical studies, updating design criteria, re-evaluating safety and structural maintenance.

The structural response of bridges to dynamic loads contains common characteristics regardless of the load type and structural system. Dissimilar to the structural response to static loads, the dynamic response of a structure depends on several parameters such as material properties, damping, mass of the structure, accelerations, velocity of moving loads and modes of vibration. Recent findings in the nature of dynamic loads and their characteristics along with the continuous improvement in construction material properties should be involved in designing new bridges and also re-evaluation of the existing structures.

Using probabilistic approaches (in compare to deterministic approaches) is an efficient way to provide a better balance between cost and safety. By integrating the uncertainty of load characteristics, material properties, etc. code developers and designers have found a more reliable method to design structures and reduce possible environmental, economic and social damages.

ISSN 2349-4506
Impact Factor: 2.545
Global Journal of Engineering Science and Research Management

VULNERABILITY OF EXISTING BRIDGES IN THE INDIA

Current Status of Existing Bridges in the India

Determining the existing condition of bridges is a key term in evaluating their response and vulnerability to different dynamic loads. With regard to the dynamic response of bridges (especially when resonance is a point of concern), in situ structural condition is important for new and aging bridges. About 54 bridges are currently in service in the INDIA transportation network.

This is a list of India's bridges longer than 500 meters (1,640 ft.) sorted by their full length above water. (https://en.wikipedia.org/wiki/List_of_longest_bridges_above_water_in_India)

The critical situation can be where two or more failure causes happen at the same time. For example, a structurally deficient bridge under overloading conditions can be significantly in danger of collapse. One practical procedure is forcing "live load" limits for deteriorated bridges after a careful bridge inspection until enough funding is provided to repair the bridge, or other decisions for its functionality is made. However, this act does not protect bridge structures against environmental disasters and accidents. Regular inspection plans and bridge rating processes have considerably reduced the risk of failure for the huge number of aging bridges in the India.

Fig.1 Bandra Worli Sea Link from Worli Sea Face

Their study shows the results of different bridge rating methods as permitted by AASHTO's manual for bridge evaluation (AASHTO, 2008b) including allowable stress, load factor and load and resistance factor method can estimate different rated capacities for the same bridge structure. However, their study considers everyday loading condition (including permanent gravity loads and vehicular loads) for common highway bridges in Georgia such as reinforced concrete tee, prestressed concrete and steel girder bridges. Most dynamic loads such as earthquake loads were not reflected in the proposed guidelines.

Dynamic Loads and Bridge Failure

Bridge failures may happen at any stage of the bridge life time as reported in the India. Reports declare collapse of older bridges, newly designed bridges, and even those which are under construction. Deterioration of the bridge elements and inadequate design criteria in older codes can be two main reasons for collapse of old bridge structures. After few bridge failures in the India (Fig. 2-3), bridge inspection and rating policies were developed in late 2000s to mitigate future disasters. The bridge inspections and ratings can highlight vulnerability of existing bridges and help authorities to make the best decision at the right time to avoid possible failures.

Fig.2

Fig.3

Beside deterioration and lack of regular inspection and maintenance, design errors and unpredicted loads can also cause collapse of bridges including new and/or old bridge structures. Hydraulic loads, collision, overloading, deterioration, earthquake and construction have been measured as the most destructive causes of bridge failures in the India.

The presence of two or more causes at the same time can significantly increase the failure threat. For example, deteriorated elements subjected to overloads or earthquake excitations might be a source of damage and possible structural collapse. After each major earthquake event, numerous reports and research articles are frequently published base on field studies and observations. In some cases, field studies reveal the need of justifying design codes to prevent future disasters (Sun et al., 2012; Yashinsky, 1998). Experimental and analytical studies on bridge failures during earthquake events can be used to investigate the adequacy of seismic codes and propose justified criteria (Cruz Noguez & Saiidi, 2012).

SEISMIC LOADS

Seismic Loads on Global Bridge Structures

Bridges, as a sensitive and relatively expensive part of the transportation networks, are critical to function after natural disasters such as earthquakes. Similar to other types of structures, bridges can be significantly damaged by large scale earthquakes. The unique structural configuration of bridges requires special attention to their dynamic response and characteristics. Numerous analytical and experimental studies are being accomplished every year to disclose particular issues regarding seismic response of bridges such as geotechnical considerations, analysis approaches, design philosophies, seismic damage assessment, retrofitting practices, energy dissipation techniques and soil structure interaction.

Each particular research can be useful in determining general trends in the structural response of bridges to be applied for new designs and evaluating other similar bridge structures. However, irregularity and complexity of some particular bridges necessitates them to be evaluated case by case. Special attention should be made for each site seismicity, system response and individual component behaviours.

Seismic Load Effects on Bridge Components

Most sensitive bridge components may include pier columns, abutments, bearings and foundations. In some specific cases, such as large vertical excitations, bridge superstructure and girders might be damaged as well. Plastic deformation of pier columns can occur in either longitudinal or transverse direction. It is desired to provide sufficient ductility by considering special seismic considerations in columns. The ductile behaviour helps to transfer applied loads to other structural components before failure, while reduces the actual seismic loads by dissipating applied energy.

Using energy dissipating devices and isolation bearings can significantly reduce the damage on bridge substructure components including columns, abutments and foundations. In areas with less seismic concerns, fixed bearing devices are still being used in highway bridge construction.

Insufficient longitudinal girder seat length is a common defect in older bridges in the India which can cause in unseating of girders and eventually bridge failure (Wright et al., 2011). In addition, large vertical accelerations during an earthquake can cause outsized bending moments larger than girders capacity and lead to superstructure failure (Fig. 2-3). As the seismic loads were traditionally being considered for two horizontal directions, this fact shows the importance of vertical accelerations and the need of particular investigation of irregular bridges such as curved and skewed bridges.

Fig. 4 Plastic deformation of a bridge concrete column

Fig. 5 A superstructure failure

Fragility Analysis of Highway Bridges

A fragility curve is the conditional probability that the structure or structural component sustains the specified damage-level or limit state for a given ground motion intensity. Assuming lognormal distributions for the probabilistic seismic demand model and the structural capacity, fragility curves are determined from equation.

$$P\left[\frac{D}{C} \geq 1 \mid IM\right] = \Phi\left(\frac{Ln(E\hat{D}P/S_c)}{\sqrt{{\beta_{D|IM}}^2 + {\beta_c}^2}}\right)$$

in which EĎP is the median of demand at the selected IM, Sc. is the median of the selected limit state, D|IM is the logarithmic standard deviations of demands and $^{\beta}C$ is the logarithmic standard deviation of the limit state (capacity).

Fragility curves can be developed for structural components as well as for the structure as a whole system. By considering variability in seismic inputs, structure response, and material capacity into account, component fragility curves are useful tools to identify weak parts of the structure and to guide for the efficient allocation of funds to strengthen or retrofit an existing structure while system fragility curves are useful in seismic risk assessment of the structure.

Fragility of Typical Straight Bridges

Several attempts have been made to develop fragility curves for different types of existing straight bridges (Choi & Jeon, 2003; Choi et al., 2004) and retrofitted bridges (Padgett & DesRoches, 2006; 2008; 2009). The most possible damages were observed in bearings, abutments and pier columns.

In seismic damage assessment of bridges, the difference between design assumptions and as-built parameters can significantly affect the estimation of demand and capacity. Multi-span curved bridges are even more sensitive to as-built details due to their more complicated dynamic response (Mwafy et al., 2007). However, as-built parameters are not deterministic and follow a probabilistic random distribution function. Random variables are not only materials and geometry of the structure, but also soil properties, dead and live load values and earthquake intensity and direction (Nowak & Collins, 2000). In practice, to generate several probabilistic structural models for fragility analysis, Latin Hypercube method is widely used (Olsson & Sandberg, 2002; Ayyub & Lai, 1991). More details regarding the response of multi-span continuous steel bridges, calculated by others are presented in following sections to compare with the examined curved bridge response.

Curved Bridge Structures

Curved bridges need more attention than straight bridges, as a result of their irregularity and unknown modal behavior (Mohseni & Norton, 2011). The uneven stiffness distribution in different horizontal directions can cause severe damage to bridge components, depending on the direction of earthquake excitations. In addition, eccentricity in superstructure weight and accompanying live load could be an issue in vertical ground excitations.

Seo and Linzell (2012) have recently studied the seismic vulnerability of an existing inventory of horizontally curved, steel, I-girder bridges located in Pennsylvania, New York and Maryland. Selected bridges were all without skew. The focus of their study was an evaluation of the Response Surface Meta-models technique in conjunction with Monte Carlo simulation. This methodology effectively reduced the number of samples for fragility analysis. However, no comparison was made to other efficient techniques such as Latin Hypercube method. Results declared that for non-skew curved bridges, bearing radial deformation was the most fragile component in extensive to complete damage states.

Case Study: Fragility Assessment of a Multi-span Curved Bridge
Horizontally curved bridges are a common practice in urban areas. The irregular geometry makes seismic response of curved bridges more dependent to bridge characteristics. To study the fragility of curved bridges and comparing the results with the same structural system in straight bridges, an existing multi-span curved bridge with continuous steel composite girders was examined against earthquake excitations. To follow a relatively reliable approach for seismic damage assessment of the bridge, fragility analysis was applied. This method assists to include the effect of uncertainties in loading/modelling assumptions. Three dimensional nonlinear finite element (FE) models were used to achieve more accurate analysis results in compare to simplified methods. Applying Latin Hypercube method, 60 different bridge models were generated considering uncertainty of each random parameter. Using the analysis results, probabilistic seismic demand models are developed for various bridge elements and fragility curves for each monitored element are plotted for considered qualitative damage levels. Furthermore, system fragility curves are presented for the bridge structure in terms of upper and lower bounds. Analysis results declare the importance of various parameters including bridge geometry and ground motion direction, and also their impact on analysis results. Also, the bridge superstructure stayed elastic during vertical excitation with relatively high PGA's. Median PGA values which cause slight, moderate, extensive and complete damages were determined equal to 0.09g, 0.19g, 0.29g and 0.57g, respectively.

ANALYTICAL MODELLING AND RESULTS
The methodology for the generation of seismic fragility curves, as presented in the previous section, is illustrated using a class of highway bridges common to the CSUS. The selected bridge type is a multi-span simply supported (MSSS) concrete girder bridge. A detailed review of the concrete girder bridges in the national bridge inventory (NBI) shows that the MSSS concrete girder bridges account for approximately 19% of the highway bridges which is the single largest bridge class the region. This case study develops generalized fragility curves for this class of bridges and not for a specific bridge.

Bridge description and modelling
Over 81% of the MSSS concrete girder bridges were built prior to 1990, which is indicative of limited seismic detailing and their relatively small use in current construction. To give an idea of typical geometric properties of this bridge class, empirical cumulative distribution functions (CDFs) are generated and shown in Figure 1. The span lengths for over 90% of this bridge type fall in the range of 6–25 m. The 90th percentile for the deck widths and column heights are around 13 and 7 m, respectively. The most likely number of spans is three with a probability of 42% and over 83% of all bridges fall in the range of 2–5 spans. The skew is 0◦ for over 70% of the bridges and over 86% of all the bridges have a skew which is less than 30◦.

By sampling on the information from the inventory analysis, eight representative (not actual) bridge configurations are defined. These sample bridges have three spans with 0◦ skew and have the geometric properties listed in Table I. Figure 6 presents the generic layout of this bridge type.

Details for this bridge type are taken from bridge plans for several existing bridges located in Memphis, TN. The appropriateness of applying these details to the general class of MSSS concrete girder bridges is justified in previous studies. These bridges generally use multi-column bents which are founded on driven pile foundations with eight piles under each footing. The bridge ends are supported by pile-bent abutments. The superstructure is constructed of concrete girders and a concrete deck. These bridges typically use elastomeric pads for bearings.

Steel dowels are placed in the top of the bent beam and extend into the underside of the concrete girders to act as girder restraint devices. Expansion in the deck is accommodated by providing slotted holes in one end of the girder.

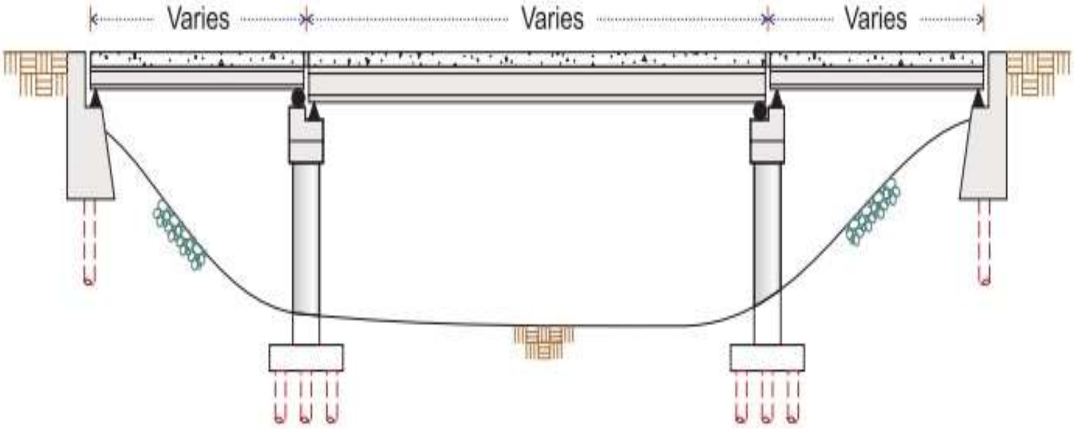


Fig.6

Using the Open Sees analysis platform, detailed non-linear 3-D models are created for each subject bridge. A brief description of the analytical modelling procedure is given in this paper. However, for a full treatment of the analytical models see the work by Nielson.

The superstructure, which refers to the composite slab and girder section, is expected to remain linear and is thus modelled using linear elastic beam–column elements. Pounding between the decks is accounted for using the contact element approach including the effects of hysteretic energy loss which is outlined in the work by Muthukumar and DesRoches. Damping is accounted for in the model using Rayleigh damping but is treated as a random variable (see Table).

Table I. Uncertainty incorporated in analytical bridge models

Modelling parameter	Probability distribution	Distribution parameters 1	Distribution parameters 2	Units
Steel strength	Lognormal	$\lambda = 6.13$	$\zeta = 0.08$	MPa
Concrete strength	Normal	$\mu = 33.8$	$\sigma = 4.3$	MPa
Bearing shear modulus	Uniform	$l = 0.66$	$u = 2.07$	MPa
Bearing coefficient of friction	Lognormal	$\lambda = \ln(\text{med})^*$	$\zeta = 0.1$	
Passive stiff of abutments	Uniform	$l = 11.5$	$u = 28.8$	kN/mm/m
Active stiffness of abutments	Uniform	$l = 2.2$	$u = 6.6$	kN/mm/m
Translational foundation stiff	Uniform	$l = 28$	$u = 84$	kN/mm/ftg
Rotational foundation stiff	Uniform	$l = 3.03(10)^5$	$u = 9.09(10)^5$	kN m/rad
Deck mass	Uniform	$l = 0.9^\dagger$	$u = 1.1$	
Damping ratio	Normal	$\mu = 0.045$	$\sigma = 0.0125$	
Internal hinge gaps	Normal	$\mu = 25.4$	$\sigma = 3.3$	mm
Abutment–deck gaps	Normal	$\mu = 38.1$	$\sigma = 1.01$	mm
Loading direction	Uniform	$l = 0$	$u = 2\pi$	radians

ISSN 2349-4506
Impact Factor: 2.545

Global Journal of Engineering Science and Research Management

All dissimilar nonlinear 3D models were subjected to direct integration time history analysis, using finite element based software SAP2000® (2009). P-delta effect and justified damping ratio were taken into account for each time history analysis.

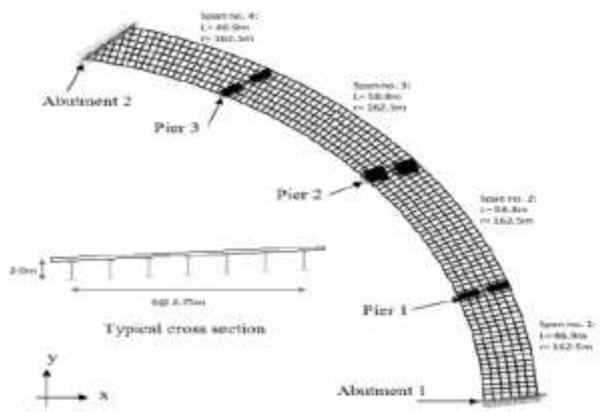


Fig.7 General Plan and typical cross section of the existing curved bridge

Foundation modelling

A cohesive soil profile was observed in boring test results at pile locations. One row steel driven piles at abutments are rigidly connected to steel girders among a reinforced concrete pile bent. To include adjacent soil effects, equivalent stiffness of backfill soil was calculated for each abutment neglecting the effect of the approach slab and thin concrete slop protection in front of each abutment (Buckle et al., 2006). For this reason, 0.24 MPa passive pressure was considered in calculating equivalent soil stiffness at abutments. By using nonlinear gap elements in SAP2000© models, the backfill soil stiffness was imposed during passive displacements only (Fig. 8). Also, to include soil structure interaction in 3D models, equivalent stiffness for each H section steel pile was provided at location of each pile in all directions (Fig. 8). Stiffness values were subject to change in different models according to uncertainty in soil properties. Passive pressure from adjacent soil at each pier pile cap was also taken into account using line springs along pile cap edges (Buckle et al., 2006). Piles group action at abutments and piers were included due to the actual modelling of pile caps and abutments.

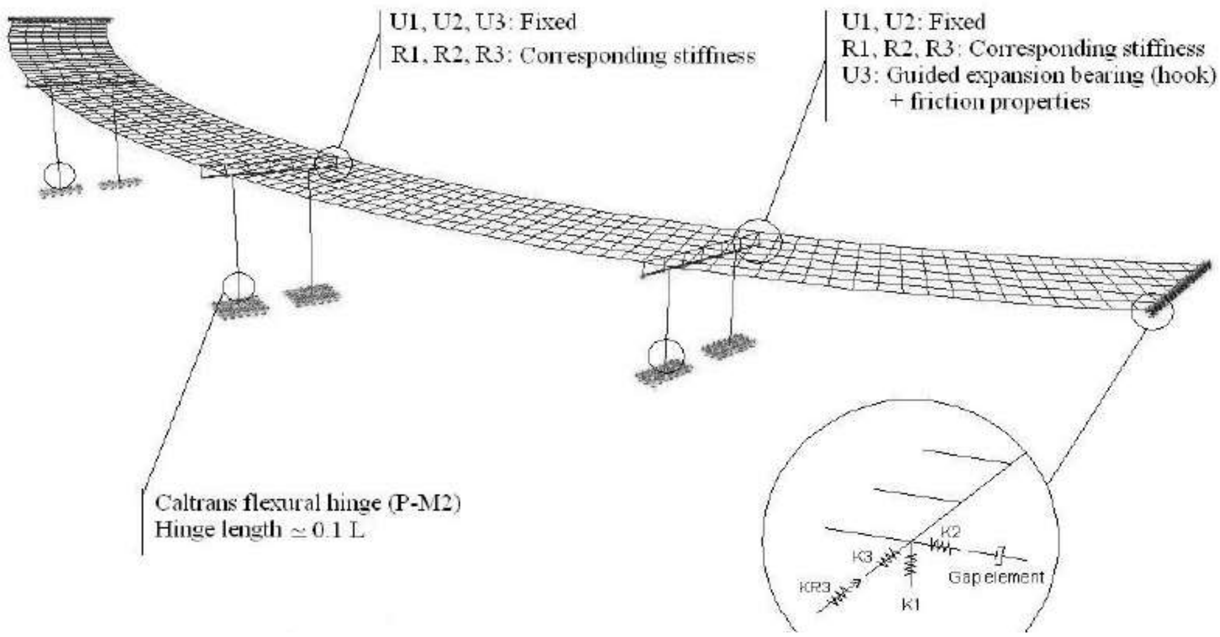
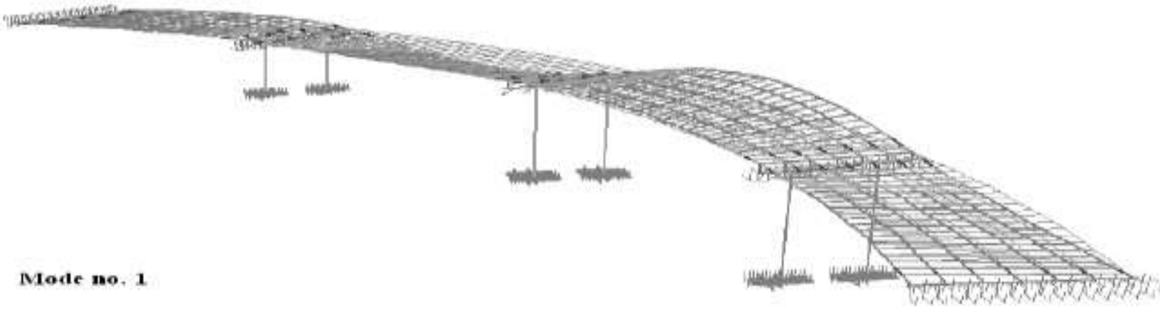
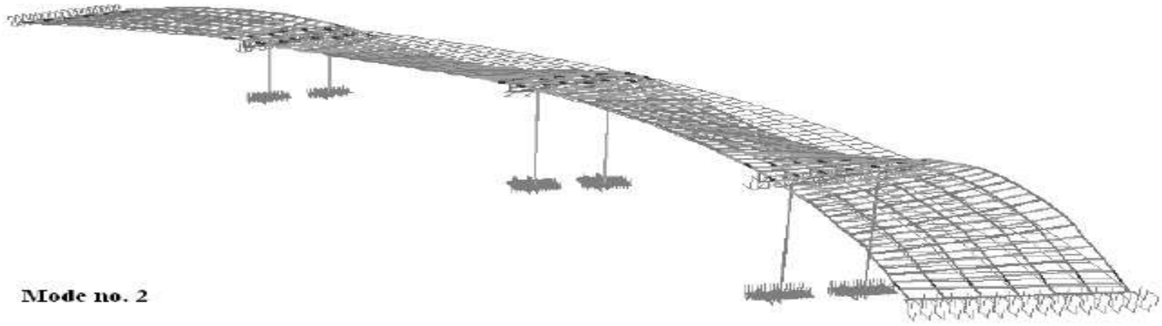


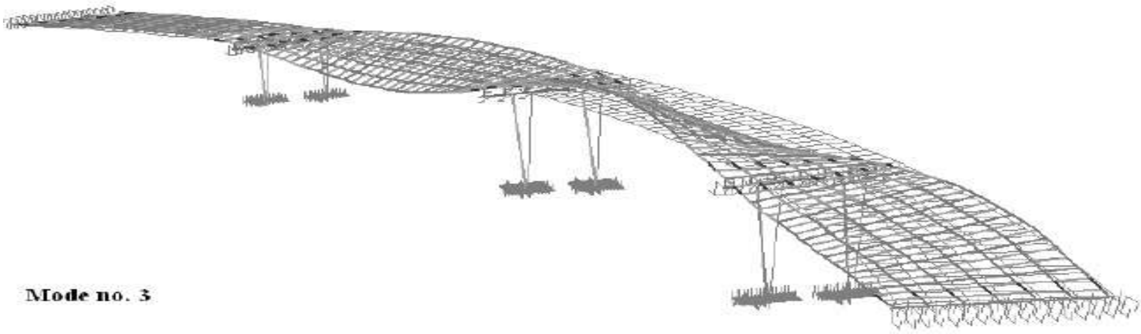
Fig. 8 SAP2000© model for entire bridge using grid system for superstructure



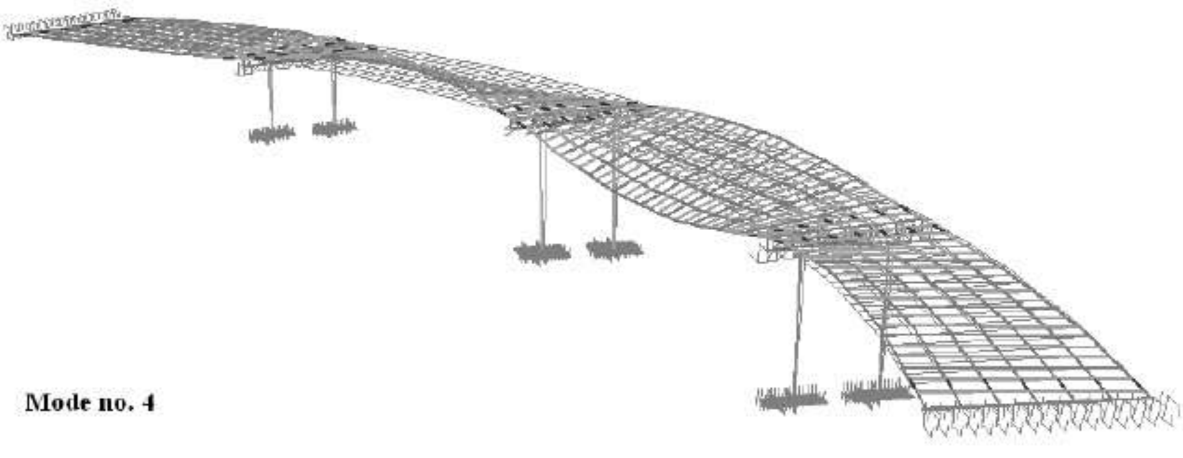
Mode no. 1



Mode no. 2



Mode no. 3



Mode no. 4

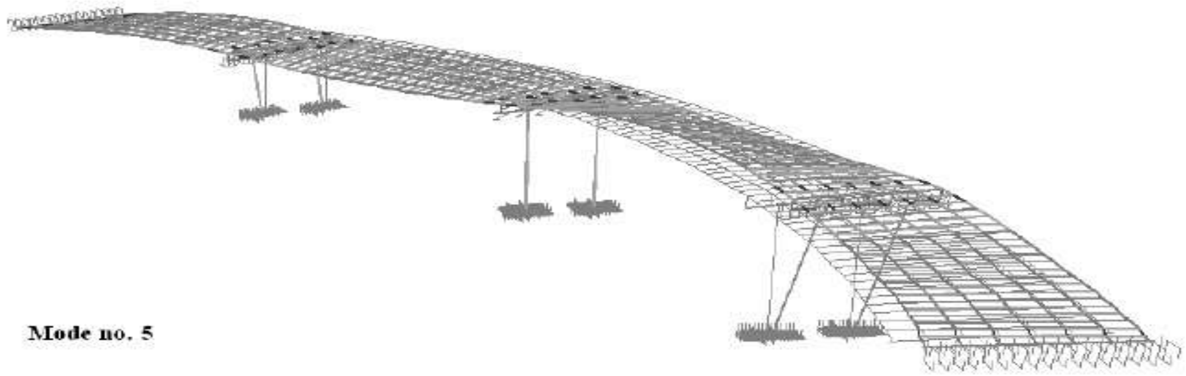


Fig.9 Predominant modal shapes

Based on modal analysis results (Fig. 9), the first two mode shapes were vertical vibration and swinging of the bridge superstructure due to the existence of long spans and eccentricity. Nevertheless, the bridge superstructure did not show any plastic response against vertical ground motions. The next three predominant modes (3, 4 & 5) declared horizontal movement of the bridge superstructure which causes the most damages in pier columns and abutments.

RESULTS

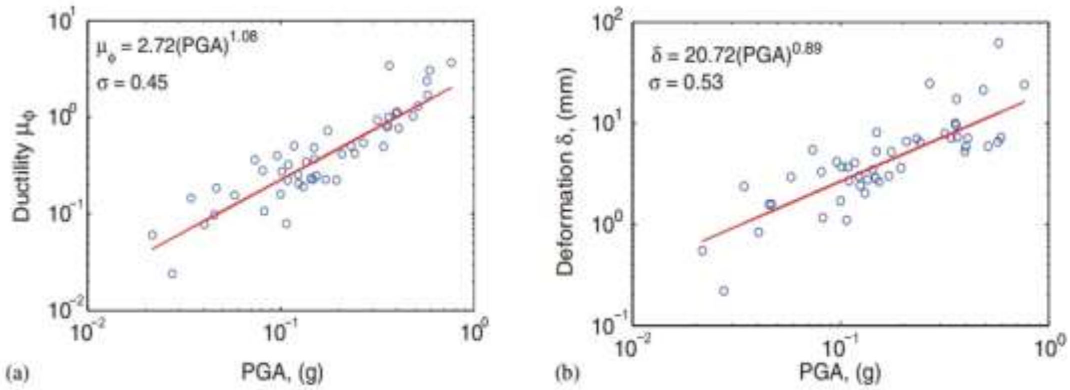


Fig 10. Probabilistic seismic demand models for: (a) columns; and (b) abutments.

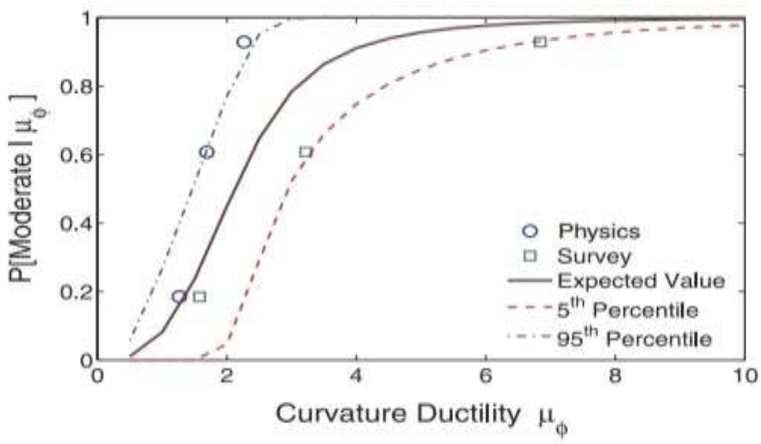


Fig 11. Bayesian updating of distributions of moderate damage state for columns.

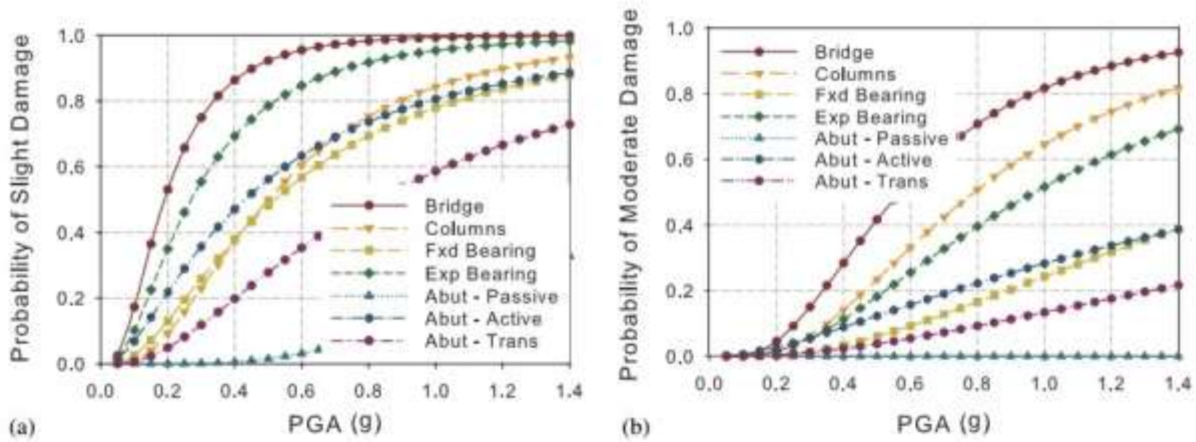


Fig12. Bridge and component fragility curves for: (a) slight damage; and (b) moderate damage

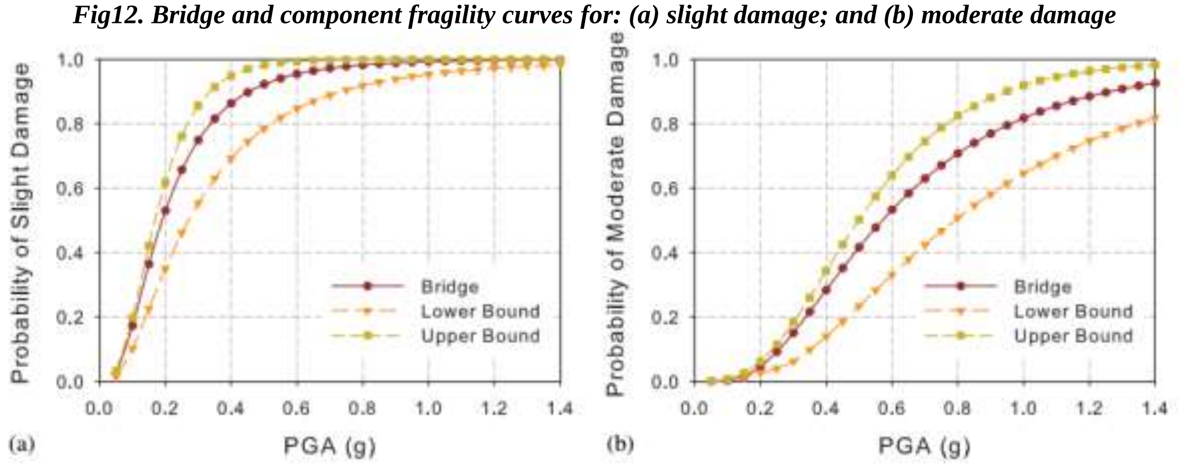


Fig13. Bridge and system fragility bounds for: (a) slight damage; and (b) moderate damage.

CONCLUSION

This study presents an analytical methodology for developing seismic fragility curves for highway bridges. Specifically, this methodology is designed to provide consideration of all major bridge components in assessing seismic vulnerabilities. The demand on the bridge is quantified by using a JPSDM. The fragility of the bridge is calculated by integrating over all failure domains of the joint PSDM. Probabilistic models for the capacities are assumed to be lognormal and are used to define the failure domains of the JPSDM.

A case study illustrating this technique of directly calculating seismic bridge system fragility curves is presented for a MSSS concrete girder class of bridges. The subject bridge class is represented by a suite of 3-D analytical models which are subjected to a suite of synthetic ground motions. The results from these analyses are then used to generate the joint PSDM needed by the proposed methodology. The bridge components considered in the development of this joint PSDM include the columns, bearings and abutments. Once the PSDM is defined, along with appropriate capacity models, the fragility models for this particular bridge could be calculated.

The resulting fragility curves for both the bridge components and the bridge system as a whole show that the bridge system is more fragile than any one of the bridge components. For the slight damage state, the expansion bearings are calculated to be the most fragile with a median value of 0.19g. The bridge system for the same damage state is calculated to be 0.09g showing a difference of 42%. For the moderate damage state, the columns are seen to be the most fragile of the components with a median value of 0.57. This compares with the system fragility having a median of 0.29g and a resulting error of 39%. This illustrates that using the fragility of any single bridge component to represent the overall vulnerability of the bridge would likely result in a significant underestimation of that vulnerability.

First-order bounds on the system fragility curves were also developed to provide comparison with the fragilities calculated using the direct estimation procedure presented in this study. The largest discrepancies occurred between the directly calculated fragilities and lower bound estimates. Errors resulting from using the lower bound as the estimate of the system fragility are greater than 40%. The errors between the system fragilities and their upper bounds are approximately 10%. The analysis presented in this study, has considerable epistemic and aleatory uncertainty associated with it. The methodology presented in this paper is relatively straightforward in its implementation and is an effective means of decreasing the epistemic uncertainty in the analysis.

ACKNOWLEDGEMENTS

The Authors thank the management of Malwa Institute of Science & Technology, Indore, Madhya Pradesh, India & Indore Institute of Science & Technology, Indore, Madhya Pradesh, India for providing materials and laboratory facilities to carry out this work.

REFERENCES

1. Yamazaki F, Hamada T, Motoyama H, Yamauchi H. Earthquake damage assessment of expressway bridges in Japan. Technical Council on Lifeline Earthquake Engineering Monograph 1999; 361–370.
2. Jernigan JB, Hwang H. Development of bridge fragility curves. 7th US National Conference on Earthquake Engineering, EERI: Boston, MA, 2002.
3. Mander JB, Basoz N. Seismic fragility curve theory for highway bridges. 5th US Conference on Lifeline Earthquake Engineering. ASCE: Seattle, WA, U.S.A., 1999.
4. Choi E, DesRoches R, Nielson B. Seismic fragility of typical bridges in moderate seismic zones. Engineering Structures 2004; 26:187–199.
5. Karim KR, Yamazaki F. A simplified method of constructing fragility curves for highway bridges. Earthquake Engineering and Structural Dynamics 2003; 32:1603–1626.
6. Mackie KR, Stojadinovic B. Post-earthquake functionality of highway overpass bridges. Earthquake Engineering and Structural Dynamics 2006; 35:77–93.
7. Hwang H, Jernigan JB, Lin Y-W. Evaluation of seismic damage to memphis bridges and highway systems. Journal of Bridge Engineering 2000; 5:322–330.
8. Mackie K, Stojadinovic B. Fragility curves for reinforced concrete highway overpass bridges. 13th World Conference on Earthquake Engineering, Vancouver, BC, Canada, 2004.
9. Shinozuka M, Feng MQ, Kim H-K, Kim S-H. Nonlinear static procedure for fragility curve development. Journal of Engineering Mechanics 2000; 126:1287–1296.
10. Choi E. Seismic analysis and retrofit of mid-America bridges. Ph.D. Thesis, Georgia Institute of Technology, 2002.
11. Hwang H, Liu JB, Chiu Y-H. Seismic fragility analysis of highway bridges. MAEC RR-4, Center for Earthquake Research Information, 2000.
12. Schrage I. Anchoring of bearings by friction. Joint Sealing and Bearing Systems for Concrete Structures, World Congress on Joints and Bearings, American Concrete Institute, Niagara Falls, NY, U.S.A., 1981.
13. Caltrans. Caltrans Seismic Design Criteria (2nd edn). California Department of Transportation: Sacramento, CA, 1999.
14. Rix GJ, Fernandez-Leon JA. Synthetic Ground Motions for Memphis, TN, 2004 [cited July 2, 2004]; Available from: http://www.ce.gatech.edu/research/mae ground motion