FRAGILITY CURVES IN DYNAMIC ANALYSIS OF BRIDGES UNDER HAZARDOUS LOADING

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Abstract

Highway bridge networks may be exposed to a wide range of hazards during the course of their life. The damage caused by these hazards may interfere in the proper functionality of the bridge during the post disaster response. Designing bridges to resist extreme hazard loads has been a major concern of the present scenario. Consideration of these hazardous loading events for the assessment of bridges would be advantageous in the development of risk resilience and restoration plans. This report aims at understanding the concept of fragility of bridges subjected to hazardous loading. The importance of the term fragility is emphasized with respect to the bridge responses. Fragility is basically the susceptibility to failure under impact of external loads. The fragility analysis of bridges can be done using various methods involving probabilistic approach. Fragility models which depict the fragility of the bridges in the form of fragility curves and surfaces, can be effectively used to assess the performance of bridges during hazardous events. Various literatures available in fragility-based assessment of the dynamic response of bridges to hazardous loading are considered in the paper. These fragility curves developed can be efficiently employed in pre and post-hazard risk, resilience and restoration practices. Various combinations of natural and manmade hazards are yet to be explored in the fragility-based assessment of bridges under multiple hazards

Keywords: Hazards, Fragility, Highway Bridge, Multiple Hazard, Disaster Response

I. INTRODUCTION

Bridges are important components of highway transportation networks since they facilitate an efficient commerce and communicating system between cities and also across the country. However, these bridges can be very susceptible to damages induced by multiple hazards during their life span. These hazard cases may either be natural or man-made. Among these hazards earthquakes, floods, hurricanes are the costliest and have known to impart severe damage to bridges across various regions. Bridge damage from such hazardous events causes severe interferences to emergency response and the socioeconomic recovery. In recent scenario emphasis is more on building and maintaining sustainable infrastructure where components are expected to remain functional during these types of hazards. This increased awareness on the vulnerability of highway bridges to multiple hazards has led to a growing interest among researchers in the field of multiple hazard assessment of bridges. The predominant need for the safety and serviceability of the critical transportation system requires highway bridges to be analyzed and designed not only for individual hazard events, but also for multiple hazard conditions. The above-mentioned practice of assessment of various bridges can facilitate pre-hazard and post-hazard event mitigation and emergency response strategies. Here comes the role of fragility models in the analysis of bridge structures. These fragility models help in the quantification of possible damage levels that bridges suffer when exposed to a range of hazard cases. The fragility models thus developed can be effectively used in mapping the vulnerability of the bridge to these hazardous events. From this mapping, appropriate recovery patterns can be deduced to quantify restoration times and ultimately resilience using restoration models. This paper basically focuses on fragility dependent dynamic response of highway bridges. The fragility of bridges in the case of hazardous events is an essential criterion of emphasis that has emerged in the present world. The report helps in identifying the importance of considering the fragility of bridges to various natural and man-made hazardous situations. Through the various literatures under focus of this report, the role of fragility models in individual and multiple hazard scenarios can be identified.

II. HAZARDOUS EVENTS ON BRIDGES

In simple terms, hazard is “Any agent that can cause harm or damage to life, health, property or the environment”. These hazards may be natural or man-made which affect the bridge individually or the bridge may be affected by multiple hazards. The current specifications for the design of bridges intend to prevent collapse risk and provide minimum criteria for safety and serviceability against hazards. It could be understood through the review of literatures that these specifications are not sufficient to evaluate collapse state. Past and recent extreme events have demonstrated the vulnerability of highway bridges to hazards such as earthquakes, hurricanes, fire, storm surge, scour, impact load, overloading, aging, blast load etc. These hazardous events imply the need to develop solutions and approaches to reduce the damages caused to bridges with acceptable cost [1]. Each hazard has its own characteristics with respect to probability, frequency of occurrence, and consequences which need not necessarily be consistent with each other. This implies the need for a general probability-based framework to explore and establish multi-hazard design for bridges. This field is particularly complex and a slowly developing challenging task because of reasons such as lack of sufficient information on the characteristics and occurrence of the extreme hazards and the corresponding performances of bridges. The term fragility comes into role at this point in the multiple hazard assessment of bridges.

III. FRAGILITY

A. What is Fragility?

Basically, the term fragility refers to the susceptibility of an item to breakage, failure, or loss of value from the impact of external forces, measured as the amount of force required to cause the damage.

B. Fragility Curve

Fragility curve is a statistical tool representing the probability of exceeding a given damage state as a function of an engineering demand parameter [2]. Fragility curves can be used for decision-making in both the pre-and post-earthquake disaster events, to make decisions on the allocation of resources, design and improve the redundancy of a highway network. In the case of seismic fragility curves, the probability of a structural system reaching a limit state is expressed as a function of some measure of seismic intensity such as peak ground acceleration, pseudo spectral acceleration etc. Fig. 1 shows a typical fragility curve.

C. Fragility Analysis

In order to easily understand the concept of fragility analysis we can consider the case of earthquakes. Seismic fragility is the susceptibility to failure of a structural component or a system as a whole to perform satisfactorily under a predefined limit state when subjected to an extensive range of seismic action. Seismic fragility analysis basically is the comparison of the seismic capacity and seismic demand of the structure under consideration. It assesses whether the seismic capacity is exceeded for a well-defined performance level when the structure is subjected to specified levels of ground motion intensity. Thus, seismic fragility analysis can be regarded as a probabilistic measure for seismic performance assessment of structural components or systems.

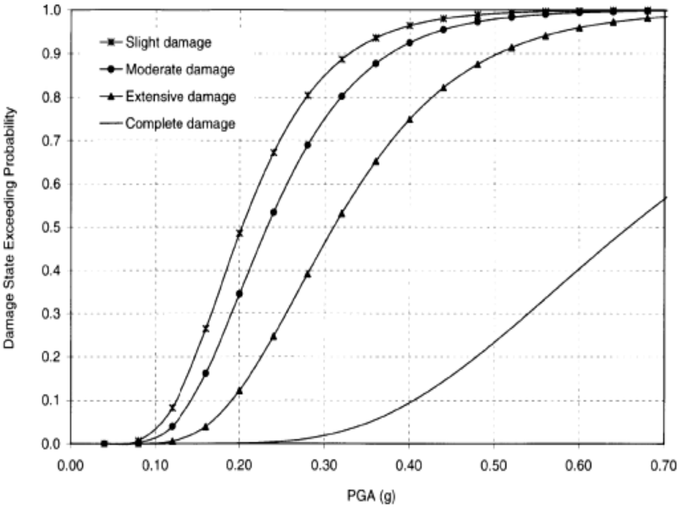

Fig. 1 A typical fragility curve under seismic loading

D. *Methods of Fragility Analysis*

Seismic Probabilistic Risk Assessment (SPRA) methodology is becoming popular wherein the key elements are seismic hazard analysis, seismic fragility evaluation for components and substructures and system analysis. In the SPRA methodology the structural reliability is described by the fragility curve. The fragility curve expresses the probability that the structure fails under seismic load or seismic Intensity Measure (IM). The methods of fragility analysis as studied by [3], are basically divided into the following

1) *Safety factor method* - Here the fragility curve is estimated based on safety margins with respect to an existing deterministic design of the structure. On this basis, seismic margins or safety factors are evaluated in order to estimate a realistic median capacity of the structure. Uncertainties related to each safety factor are also assessed. It is assumed that all safety factors follow a lognormal distribution such that the resulting seismic capacity, obtained as the product of the latter with the design earthquake, is also lognormally distributed.

2) *Numerical simulation method* – Here the parameters of the fragility curve are obtained by

    a) *Regression analysis* - This methodology is based on nonlinear time history analysis. Time history analysis is performed on the structure to obtain a data sample that can be used for the evaluation of fragility curves. Here, the seismic load is characterized by N ground motion histories in agreement with the site-specific hazard. Latin Hypercube Sampling is used to account for the variability of structural parameters (such as material characteristics) to propagate the uncertainty through the mechanical model. This method optimizes the exploration of the whole space of possible parameter values. Thus, it increases the rate of convergence and contributes to reducing the number of analysis to be performed.

    b) *Maximum likelihood estimation* – This estimation is made from a set of nonlinear time history analysis at different seismic levels. It assumes that the results are independent wherein a set of non-correlated time histories, as per seismic codes are chosen as input. This process is followed by estimating the most plausible parametric fragility curve given the binary data. One among the most adequate example for binary data was identified to be the cases were buckling is considered. However, this method has drawbacks since it requires data before and after failure and sufficient data close to the median capacity, in order to converge and produce meaningful results. If these data were found unavailable, it implied a loss of information since the estimator continuously transforms the measured damage to binary output.

3) *Incremental dynamic analysis (IDA)* – This is a method where a set of accelerograms is scaled until failure. The Incremental Dynamic Analysis is also based on numerical simulation, but here a set of accelerograms is scaled to have same intensity level. Considering the scaled set of accelerograms ‘N’, nonlinear time history analyses are performed for each intensity level. The set of ‘N’ accelerograms are scaled to increasing intensity levels, until failure is reached. Uncertainties of the structure are considered by using one set of ‘N’ uncertain parameters, to be used for all intensity levels. The IDA provides a sample (of size ‘N’) of structural capacities. Using this method, each accelerogram has a single capacity value associated with onset of collapse. The data samples obtained from the analysis is compared to the demand to generate the fragility curve.

IV. FRAGILITY MODEL

Research had been done and is still under progress in producing various fragility models for bridges under hazardous events. These fragility models are being made, considering the type of hazard to which the bridge is being exposed. The fragility models for bridges under hazards basically consists of functions involving the probability of damage and the intensity measure of the loading along with consideration of other parameters influencing the fragility. The following sections provides an overview of various available literatures on fragility-based assessment of bridge responses. The main emphasis in the study is given to seismic fragility, flood fragility and also combined hazard fragility is under consideration.

A. Seismic Hazard Fragility Model

A fragility model is a function that quantifies the conditional probability representing the likelihood that a structure will meet or exceed a specified damage state (i.e., level of damage) for a given intensity measure (IM) of the seismic hazard [2]. It is also stated that the fragility function may be conditioned on a vector of bridge structural parameters and time, such that the effects of different bridge configurations and deterioration due to aging can also be considered respectively. An expression for seismic fragility is also given in the work by [2], which is expressed as P [DS/IM, X,t], where DS is the damage state or limit state of the bridge and P[A/B] is the conditional probability of event A given B. This general form is stated to be relevant for any other natural hazard provided appropriate intensity measures and hazard-induced damage states are selected. Basically, there are some main methodologies for the construction of seismic fragility models.

In a work done by [4], various applications of seismic fragility curves were stated such as assessment of potential consequences and risk, emergency/disaster response planning, emergency route selection, risk mitigation effort. These applications would finally help towards the decision making and safety compliance of the structure. Along with applications, a detailed address to various methodologies for the development of seismic fragility curves were also discussed in the work. The main identified methods were expert based, experimental, analytical, hybrid and empirical method.

Most of the fragility models developed have come across to be time-independent because of the lack of appropriate data to characterize the time-progressive deteriorating nature of structural components. It was also identified that the development of these fragility curves was also hindered by computational constraints such as not accounting for the variation of bridge parameters, ignoring the effect of variations of other geometrical parameters etc. These limitations have finally lead to a simplified expression for the seismic fragility of bridges given by P[DS/IM], where DS is the limit state or damage state of the structure or structural component, IM is the ground motion intensity measure. It is evident from literatures that bridges with different structural configurations will have different fragilities and that deterioration effects of aging can considerably change the fragility models of these bridges.

Recent research in the bridge engineering community focus on the development of parameterized [5] and time-dependent [6] bridge fragility models. The study by [5], identified that parameterized fragility functions can be used for bridges with variations in geometric properties and structural configurations when they are exposed to different hazard types. These functions are developed from metamodels and regression analysis and can be combined with regional hazard data to evaluate risk. The variations given in design details of the bridges are captured in the fragility curves by the parametric fragility functions.

Definition of damage states describing the extent of loss of capacity of the various bridge components along with stating the damage of the bridge as a system was identified as essential for fragility model development [2].

B. Flood Hazard Fragility Model

It is a well-known fact that bridges are also exposed to a variety of flood related risk factors such as bridge scour, structural deterioration, debris accumulation etc., which cause structural damage and failure of bridges through variety of failure modes. The fragility models for highway bridges subjected individually to riverine flood are very limited. The HAZUS methodology for quantifying damage states due to flood hazard reported fragilities of highway bridges in the form of probability matrices [2]. Because of the lack of comprehensive bridge damage data due to flood hazard, it is stated that fragilities calculated based on these empirical estimates could be calibrated for different deck materials in future versions of the HAZUS methodology. In a work done by [7], reliability analysis was performed in conjunction with finite element analysis to accurately obtain the flood fragility estimates. In this method, sophisticated stimulation of structural response of bridge under flood is made possible which account for flood related risk factors. Flood fragility curves accounting for multiple failure modes were derived for an actual bridge as shown in fig 2, in the study by [7].

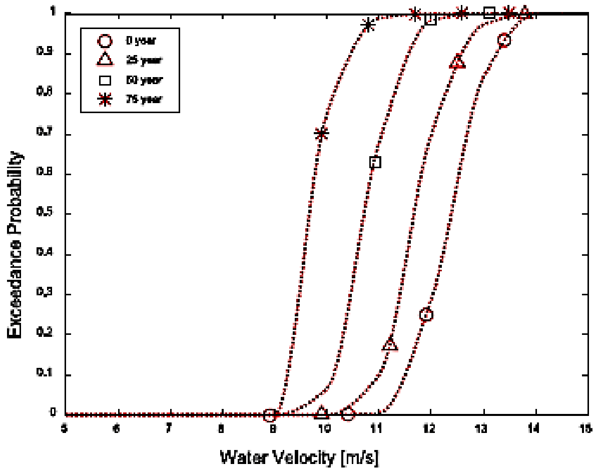

Fig. 2 Flood fragility curves for various periods of structural deterioration with deck loss (Kim et al. 2017).

As stated earlier the HAZUS method provided probability of failure values P [Failure/IM, SV] as a function of the flood return period corresponding to IM of flood hazard and the scour vulnerability (SV) rating assigned to the bridge after scour evaluation. Fig. 3 shows the occurrence of scour hole during flood. Methodologies were later proposed to determine the flood induced failure on bridges based on the bridge's span type and scour induced failure based on the adequacy of the water way crossing the bridge [2]. Studies were also conducted that emphasized on the structural failure of bridge superstructure due to flood induced lift forces.

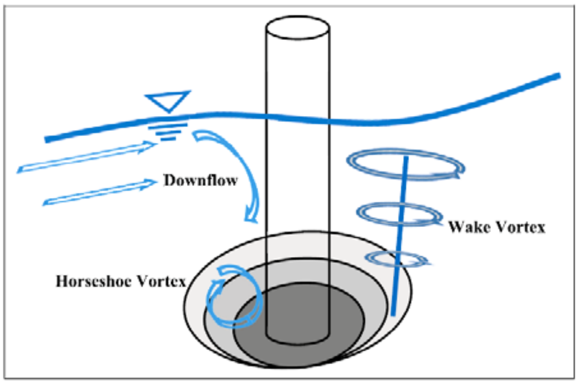

Fig. 3 Occurrence of the scour hole during a flood

(Kim et al. 2017).

C. Combined Hazard Fragility Model

Highway bridges are also frequently exposed to scenario of multiple hazard events apart from being affected by individual hazard events. These multiple hazard events might occur concurrently (e.g., earthquake and flood-induced scour) or in a cascading manner (e.g., mainshock-aftershock earthquake sequences or earthquake triggered tsunamis). The increased vulnerability of bridges to these combinations of hazards has recently stimulated the interest of researchers towards developing fragility models for multiple hazard scenarios. This study mainly focuses on concurrent hazard fragilities. From the literatures reviewed cases of earthquake and flood induced scour was the only main combination of hazards to be found taken up in the case of fragility-based assessment. It is a fact that the likelihood of occurrence of earthquake and flood simultaneously during the lifetime of a bridge is low. But it can be noted that chances of occurrence of such combinations is definitely a case of concern in earthquake prone and flood prone regions, wherein the bridge might be initially exposed to flood induced scour and then attacked by an earthquake tremor [2]. Studies have been performed with respect to this combination and fragility expressions have been deduced which can be expressed as P [DS_d/IM, IM_{scour}], where IM_{scour} is the intensity measure of the scour effect, with scour depth at bridge foundation being the most commonly adopted measure [2]. The basic meaning of this expression is that DS_d is met or exceeded conditional on given values of IM and IM_{scour}.

In a recent study by [8], derived a framework to evaluate earthquake and scour fragilities for multispan concrete box girder bridges with various number of spans. The multiple hazard performance evaluation framework presented in the study involved estimation of seismic and flood hazards of the study region, calculation of scour at bridge piers based on bridge geometry, subsurface condition and flood hazard levels, and time history analysis of bridges in the presence and absence of flood-induced scour. Results from the time history analysis were used to categorize the bridge damage states which in turn were used for the fragility curve development.

Reference [9] generated fragility curves and fragility surfaces for the four common damage states for two California concrete box girder bridges. A framework similar to the previously discussed work is applied here also. Fragility curves represented bridge vulnerability for specific combinations of flood and seismic hazards and fragility surfaces represented the same for all possible combinations of these two natural hazards. The multiple hazard performance of these two bridges was assessed by considering a flood induced scour event followed by a seismic event.

Regional seismic hazards and flood hazards were adopted for the fragility analysis of the two bridges. Seismic hazard curves developed by the United States Geological Survey (USGS) were considered for regional seismic hazard and flood hazard curves developed by flood frequency analysis method based on data from the USGS were considered for regional flood hazard. Seismic hazard curves as shown in fig. 4, provide annual exceedance probabilities of seismic events having various intensity levels whereas flood hazard curves provide peak-flow discharges corresponding to flood events having various annual exceedance probabilities.

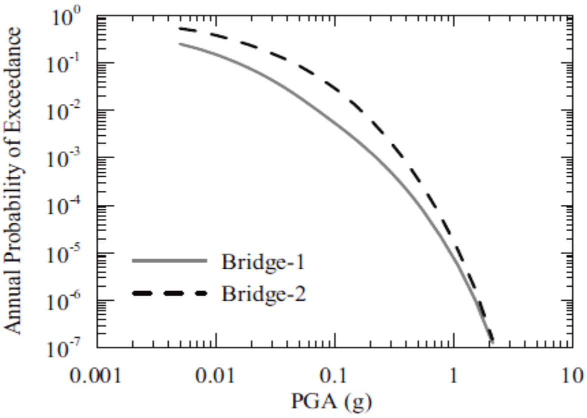

Fig. 4 Seismic hazard curves at bridge sites (Yilmaz et al. 2016)

It was recognized that scour depth is a consequence of the flood hazard, rather than the source of the hazard itself. Hence, flood return periods and peak annual flow discharge were adopted as IM_{scour} for the proposed fragility curves and surfaces, respectively. This approach allowed consideration of varying scour depths across the multiple piers of a bridge.

Flood induced scour depth (y_s in 'm') at bridge foundations were estimated by the equation

$$y_s = 2.0\, y_1\, K_1\, K_2\, K_3 \left(\frac{a}{y_1}\right)^{0.65} F_{r1}^{\,0.43},$$

where, y_1 is the flow depth at upstream of pier, a is the pier width, K_1, K_2 and K_3 are correction factors, F_{r1} is the Froude number given by $F_{r1}= V/\sqrt{(g\, y_1)}$. V and g respectively are the mean velocity of the upstream flow and the gravitational acceleration.

Finite element analysis of the bridge model was performed using the software opensees. Time history analysis of the bridges under the chosen seismic hazards were performed and responses of critical components were recorded. Based on which damage states for the bridges were proposed providing a basis for the fragility curve generation.

Here, damage states are quantitatively represented with threshold limits which are compared with results of time history analysis to develop fragility curves. A sample of the fragility curve generated for the bridge under consideration in the work is shown in fig. 5.

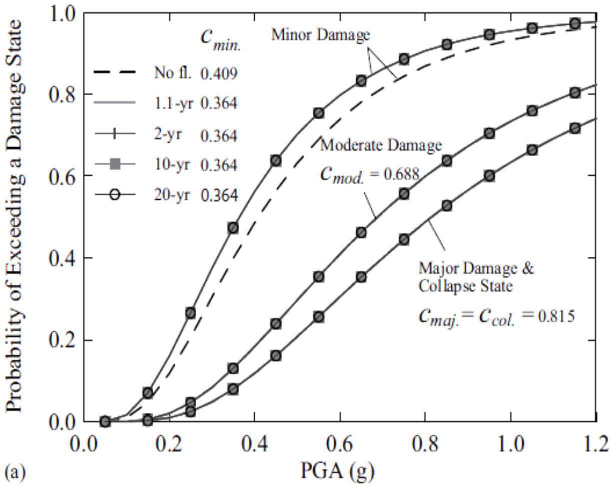

Fig. 5 Fragility curve for pier flexural damage (Yilmaz et al. 2016)

From the fragility curves obtained the piers were identified to be leading to major damage and ultimately complete collapse under the multihazard scenario.

Fragility surface were also generated which gave a comprehensive visualization of the combined effect of earthquake and flood hazards on bridge failure probabilities at various damage levels. In these surfaces hazard intensities are generally plotted along two horizontal axes, and the surface denotes the exceedance probability of a bridge damage state. A sample of fragility surface generated is shown in fig. 6. Peak annual flow discharge considered as the flood hazard intensity measure and PGA as the earthquake hazard intensity measure.

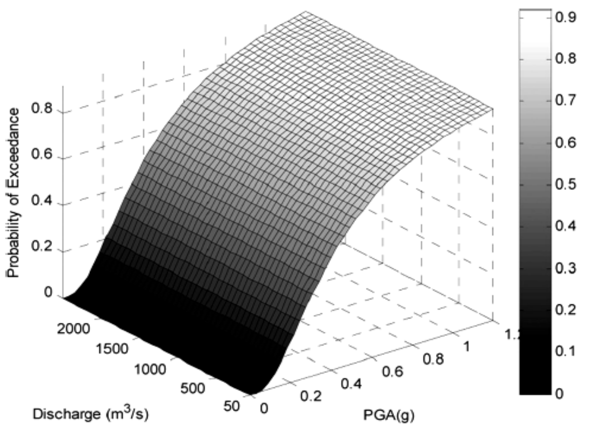

Fig. 6 A typical fragility surface (Yilmaz et al. 2016)

The results obtained show that pile shaft diameter and seismic design philosophy lead to the insensitivity of the fragility of study bridge to regional flood hazard. Increased exposed height of the bridge piers with increasing scour depth was another reason for the bridge to be more seismically vulnerable to increasing flood levels as per the study. The vulnerability information expressed in fragility curves and surfaces were identified to be useful to generate risk curves of these bridges. Finally, [10], using system reliability methods and Bayesian networks, derived fragility surfaces for a MSSS concrete bridge which were expressed as a function of peak ground acceleration and flow discharge to describe the intensity of the seismic and flood hazard, respectively. These studies open up a way to explore the possibilities of considering multiple hazard events for fragility assessment of bridges.

V. CONCLUSION

Bridges are exposed to multiple hazards during their service life. Presently bridge engineering practices rely on independent hazard models of natural and manmade hazards. Methodologies for loss estimation and risk mitigation for the bridges are developed based on their failure probabilities under individual hazard conditions. However, two extreme events may occur successively within a relatively small-time interval. These events not only cause economic losses by damaging the bridge infrastructure and other facilities but also adversely affect post disaster functionality of the bridges. Identification of major sources of risk to bridges in a region subjected to multiple hazards rather than only considering individual hazard events is vital for pre- and post-event activities. There comes the role of fragility models in the evaluation bridges during hazardous events. This report takes up the area of fragility-based assessment of bridges under hazardous loading. Initially the terms hazard and fragility are being addressed in the report which further moves on to identifying various methods for development of fragility curves. Various fragility models are discussed which can be effectively used to develop fragility curves. These fragility curves can be used in mapping the risk and restoration plans for the bridge under occurrence of hazardous events. A brief review of various works done in the area of bridge fragility is performed in the latter sections from which scope for future works can be identified.

Through this review, it has been found that, till now the works pertaining to fragility of bridges under earthquake hazard has been addressed in plenty. Whereas the consideration of fragility of bridges to riverine floods, tsunami, wind, snow etc. are relatively less. Another issue of concern is that, fragility models for manmade hazards in conjunction with natural hazards has not been given much emphasis is various studies. This is definitely an area for exploration because the chances of occurrence of manmade hazard along with natural hazard is a potential threat to the bridge infrastructure. Suppose we consider the case wherein an earthquake has occurred and people are in panic to escape to a safer zone. Since these bridges are an effective means of connection between different regions human beings would rely on them for transportation to other safer regions. The rush that might be created due to large population approaching the bridge would lead to occurrence of manmade hazards such as overloading, vehicle collision etc. Another earthquake tremor during such a situation can prove to be very disastrous to the bridge. Thus, emphasis has to be given to the occurrence of manmade hazards along with natural hazards, so as to device efficient risk resilience and restoration plans to help in pre and post-hazard mitigation. Consideration of fragility of bridges to such cases would open a way to evolve such risk resilience and restoration plans. Such studies would definitely be a boon to the area of bridge fragility under hazardous loading which in turn would contribute to pre and post-hazard risk resilience and restoration plans.

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