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The effect of earthquake ground motions parameters on bridges fragilities

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ABSTRACT

Earthquakes are one of the most destructive natural disasters that cause significant damage to structures all over the world, where the earthquakes' ground motions are characterized by different parameters such as magnitude, seismic intensity, duration, epicentral distance and angle of incidence, have an impact on the fragility of structures. In this aspect, the present work aims to investigate the effect of three significant parameters: seismic intensity, duration and epicentral distance on the seismic vulnerability analysis of the bridges by generating and comparing their fragility curves.

For this purpose, nonlinear dynamic analyses of multi-span continuous girder bridges models were carried out by including a large variability of these parameters. The seismic excitations chosen were varying from weak to strong intensities, near-fault to far-field and from short to long duration.

In order to highlight the effect of the aforementioned earthquake parameters on bridges fragilities, a comparative study of drawn fragility curves was carried out and the results will provide a reference for future seismic damage prediction.

Keywords: Bridge, Earthquake, Epicentral distance, Fragility curves, Seismic intensity.

INTRODUCTION

Earthquakes occur without warning and can happen at any time. This significant natural hazard threatens communities around the world. They are typically caused by the movement of tectonic plates and can result in shaking and ground motion that can cause damage to buildings, infrastructure, and natural environments.

Earthquake parameters are the various measurements used to describe and characterize the ground motions that occur during an earthquake. These parameters include magnitude, seismic intensity, duration, epicentral distance, and angle of incidence. Magnitude is a measure of the energy released by an earthquake, which is determined by the size of the seismic waves it generates, while seismic intensity measures the strength of the shaking felt at a particular location during an earthquake. Duration measures the length of time that the ground shakes, while epicentral distance measures the distance between a specific location and the epicenter of an earthquake. Finally, angle of incidence, which determines how the seismic wave will interact with the earth's subsurface.

Understanding these parameters is important for assessing the potential impact of an earthquake on a particular structure and for developing strategies to minimize its effects on their fragility. In this context, numerous research works were established to determine the effect of the seismic intensity [1-9], while few investigations has been conducted regarding the other parameters.

A strict number of studies has investigated the seismic fragility of various types of bridges under different ground motion intensity levels. Probabilistic methods have been widely used to assess the seismic vulnerability of bridges, and a range of intensity measures have been considered to capture the effects of different aspects of the ground motion. These studies have demonstrated that the seismic fragility of bridges is strongly influenced by the intensity of the ground motion, with bridges becoming more vulnerable as the intensity of the ground motion increases. The studies have also highlighted the importance of considering different intensity measures in the assessment of seismic vulnerability, as different measures can have different effects on the fragility of bridges. [10-11]

In addition to the effects of seismic intensity, significant duration has been studied and recommended by most of the researchers [12-18] for evaluating structural response under short and long duration motions. Where they studied the effects of different durations of ground motion on the various types of structures such as buildings [19-22], frames [23] and bridges [24-25].

In the framework of bridges these studies provide insights into the effects of earthquake duration on different types of bridges through various methods, and investigate the relationship between earthquake duration and seismic vulnerability, performance, and damage of bridges.

Based on the results provided by those researches, it is clear that the effect of earthquake duration on the fragility of bridges is a topic of considerable research interest. All the studies highlight the importance of considering earthquake duration in bridge design and assessment.

The effects of epicentral distance on different types of bridges can vary depending on various factors, such as whether the site is located near or far from the fault rupture, the local site conditions, and the type of earthquake. Researchers have used various methods to assess the effects of epicentral distance. Using computer modeling and simulation techniques, they can simulate the effects of ground motion on the bridge structure and predict the extent of damage that would occur under different conditions. They can also identify vulnerabilities in the bridge design and suggest strategies for retrofitting or strengthening the bridge to improve its resilience to earthquakes, particularly in areas near the fault rupture [10, 25-27]. Where strong ground motions from major earthquakes near urban areas in recent years have demonstrated that the near-fault ground motions are the most severe earthquake loading that structures suffer.

Although many researchers [28-29] have reported the distinctive structural response to near-fault ground motions, which are not explicitly considered in seismic design codes and guidelines.

The incidence angle of an earthquake can also have a significant impact on a bridge's fragility. When an earthquake strikes a bridge, the seismic waves can cause the bridge vibrations and movements in different directions. The angle of the seismic waves can influence the distribution of forces and the response of the bridge to the earthquake. It can also influence the amplification of seismic waves in the bridge, depending on the bridge's geometry and soil conditions. Where the increasing of amplification can increase the potential for damage.

Previous studies affirm the significant effect of the ground motion parameters on the seismic response of bridge, in terms of identifying different damage measures considering deformation or ductility. Therefore to confirm this effect for other set of bridges, this paper investigates the impact of seismic intensity, earthquake duration and epicentral distance on the seismic fragility of multi-span continuous girder bridge type.

The work presented herein deals with a comparison of seismic fragility curve resulting from a bridge analytical analysis under a suite of ground motions including a large variability of three main parameters including the seismic intensity varying from weak to strong, the epicentral distance located near-fault to far-field and the earthquake duration varying from short to long.

DESCRIPTION OF THE NUMERICAL MODEL

A typical multi-span continuous (MSC) concrete girder bridge is considered in the present work. The different bridge models selected herein are drown from a previous study entitled ‘Piers type and height effect on bridges fragilities’ [11], [30]. The geometric properties of the studied models are models are represented by three configurations as described in Table 1.

The superstructure of the elaborated models is composed of eight concrete girders and a deck made of concrete. It is supported on two or three spans that are in turn supported on two abutments and related to piers. The girders are continuous across the piers and the fixed bearings are located on the cap beams, while the expansion bearings are situated at the level of abutments.

Each bridge pier is composed of a cap beam with 1.75 x 1.60 m2 cross section, supported by three reinforced circular concrete columns that have a diameter of 1.20 mm and variable height for each bridge model configuration.

The three-dimensional analytical models of those bridge configurations are constructed with the finite element design platform CSI-Bridge that combines both geometric and material nonlinearities [31], as illustrated in Figure 1.

Shell elements were used to model the deck with three degrees of freedom. However, girders, piers and the cap beam were modeled using the frame element. The behaviour of elastomeric bearings was simulated by spring element. The material properties of the above-mentioned elements correspond to reinforced concrete properties as illustrated in Table 3.

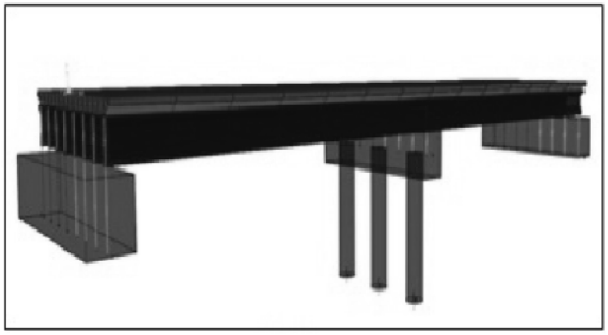


Figure 1. 3D views of typical MSC bridge models.

Table 1. Material properties of reinforced concrete.

Materials	Material parameters	Values
Concrete	Compressive strength [MPa]	27
	Tensile strength [MPa]	2 100
	Modulus of elasticity [MPa]	33 000
	Poisson's ratio	0.2
	Strain of peak stress	0.002
	Specific weight [kN/m3]	25
Steel	Modulus of elasticity [MPa]	210 000
	Yield strength	400
	Strength hardening parameter	0.005
	Specific weight [kN/m3]	78

SELECTION OF GROUND MOTION

To establish seismic analysis of selected bridge models, seismic excitation is represented by suite of 40 ground motion records from the Building Research Institute (BRI) strong motion database. The seismic data varying from weak to strong probabilistically including uncertainty in the soil and seismic characteristics. The detailed information of these ground motions is listed in Tables 2.

Table 2. Statistics characteristics for the selected earthquake records.

Earthquake Cases	Parameters	Range	Mean	Standard Deviation	CV* (%)
Weak	PGA (g)	0.04– 0.1	0.08	0.022	27.5
	Magnitude	3.8 -6.7	5.6	0.886	15.8
	Duration (s)	6 - 16	10.53	3.876	36.8
	Epicentral distance (km)	10 - 95	42.87	32.078	74.8
Moderate	PGA (g)	0.10– 0.15	0.13	0.021	16.1
	Magnitude	5.1– 7.6	6.23	0.941	15.1
	Duration (s)	6 – 27.2	13.97	70.605	50.5
	Epicentral distance (km)	13 - 123	55.41	40.363	72.8
Strong	PGA (g)	0.16 - 0,78	0.35	0.167	47.7
	Magnitude	5.2 - 9	7.5	1.053	14.0
	Duration (s)	9.5 - 90	21.59	16.583	76.8
	Epicentral distance (km)	4 - 382	150	133.282	88.8

* CV: Coefficient of variation.

As shown in Table 2, Ground motions used were recorded during seismic events where magnitudes range from 3.8 to 9, and seismic intensity is defined using the peak ground acceleration (PGA). For weak earthquakes, the peak ground acceleration (PGA) of the ground motions ranges from 0.04g to 0.10g. However, it ranges from 0.10 to 0.15 for moderate cases and from 0.16 to 0.78 for the strong cases.

In order to investigate the potential effects of ground motion duration on the seismic demands of the structures, the selected suite of ground motions can be divided on two sets, the first set of motions includes earthquake records with significant strong motion duration between 10 to 15 seconds. And the second set of ground motions contains earthquake records with a significant duration equal or more than 15 seconds. The first group of motions can represent the short-duration earthquakes while the second one is related to a dataset that includes long-duration ground motions [32].The rang of duration considered for all the ground motions selected for this study is between 6 and 90s.

According to epicentral distances, near-fault and far-field ground motions can be considered. So pursuant to CALTRANS (2004), if the structure under consideration is within 10 miles (approximately 15 km) of a fault, it can be classified as near-fault, contrariwise if ground motions having a epicentral distance of more than 10 miles are classified as far-field motions. The epicentral distances of all ground motions selected herein range between 4 and 382 km.

Figure 2 shows the individual response spectra for 40 selected earthquake records and their mean response spectrum with 5% damping ratio of the recorded ground motions. As it can be seen in this figure, dispersion of acceleration spectra of these ground motions is very noticeable which can also cause a considerable dispersion in the structural responses. This variability can be attributed to the amplitude and frequency content of the ground motions. Where it can reveal that the selected earthquake ground motion records are well describing the weak to strong intensity earthquake motion histories.

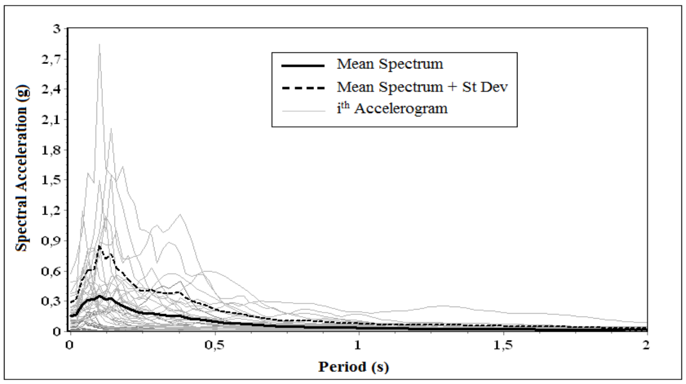


Figure 2. Individual response spectra for 40 selected ground motions and their mean response spectrum.

FRAGILITY ASSESSMENT

In order to study the effect of the aforementioned earthquake ground motions parameters on bridges vulnerability, a comparison on the seismic fragility of the generated models is drawn up. To develop fragility functions, the relationship between peak seismic responses and ground motion intensities is required, which is provided through probabilistic seismic demand models (PSDMs).

Seismic fragility curves are determined for each bridge model based on top piers seismic responses by defining the peak displacements. Assuming a lognormal cumulative distribution with respect to the median of seismic intensity (PGA), the fragility curves for different bridge models in terms of top pier responses were generated using "Equation 1" and calibrating for each considered limit state.

$$\text{Fragility} = \Phi\left[\frac{\ln(S_d/S_c)}{\sqrt{\left(\beta^2_{d/IM} + \beta^2_c\right)}}\right] \tag{1}$$

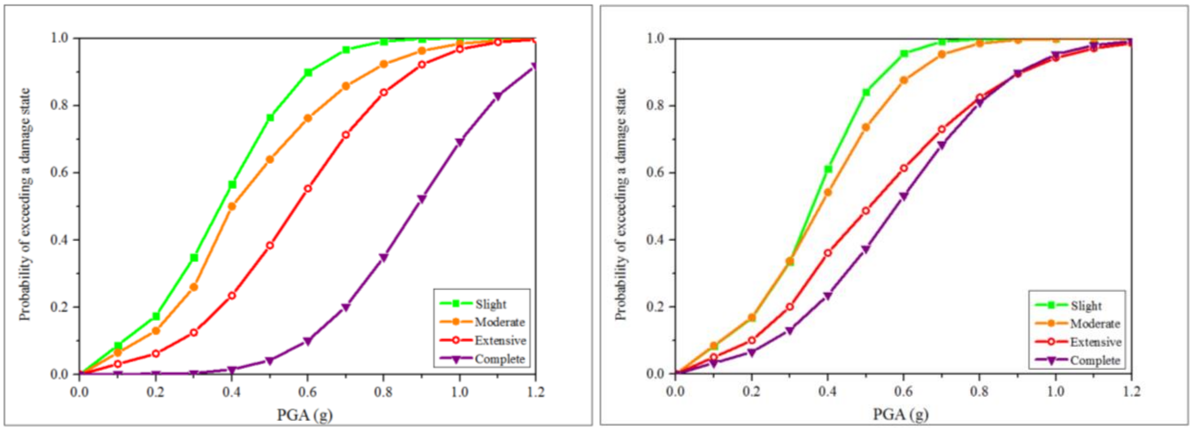
Where Sd is the median estimate of the demand as a function of IM, Sc is the median estimate of the capacity, βd/IM is the dispersion or logarithmic standard deviation of the demand conditioned on the intensity measure, βc is the dispersion of the capacity, and Φ is the standard normal cumulative distribution function.

Limit states are defined in term of acceptable degree of damage and are related to the functionality of the bridge and its components. The limit states are generally defined in a qualitative and quantitative way. Based on HAZUS-MH work, the damage states applied in this study are qualitatively described as slight, moderate, extensive, and completely damaged (FEMA 2003). The limit states quantified in this work correspond to the deformation of the fixed bearing placed in the top of pier. A quantitative value is assigned to each limit state for this bridge component as detailed in Table 3, these values were derived from Choi's study. [33]

Table 3. Bearings quantitative limit states. [33]

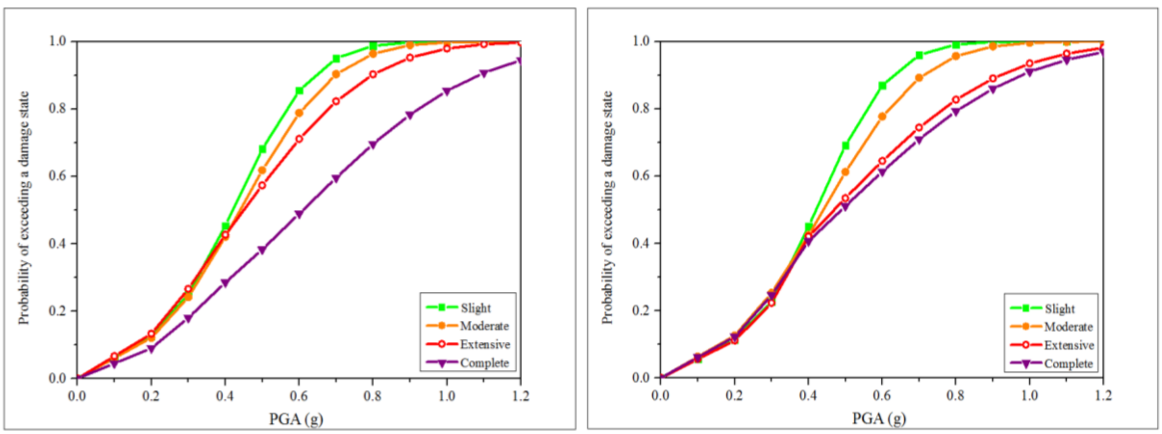
Components	Limit state (Deformation δ, mm)	No damage	Slight damage	Moderate damage	Extensive damage	Complete damage
Bearings	Fixed bearings	δ<1	1<δ<6	6<δ<20	20<δ<40	40<δ

Based on the results computed from extensive nonlinear time history analyses, the top pier displacements of the three studied bridge models were recorded for both longitudinal and transverse directions. Then the fragility curves are generated for all four damage states, where they are illustrated for each considered parameters in Figures 3, 4 and 5.



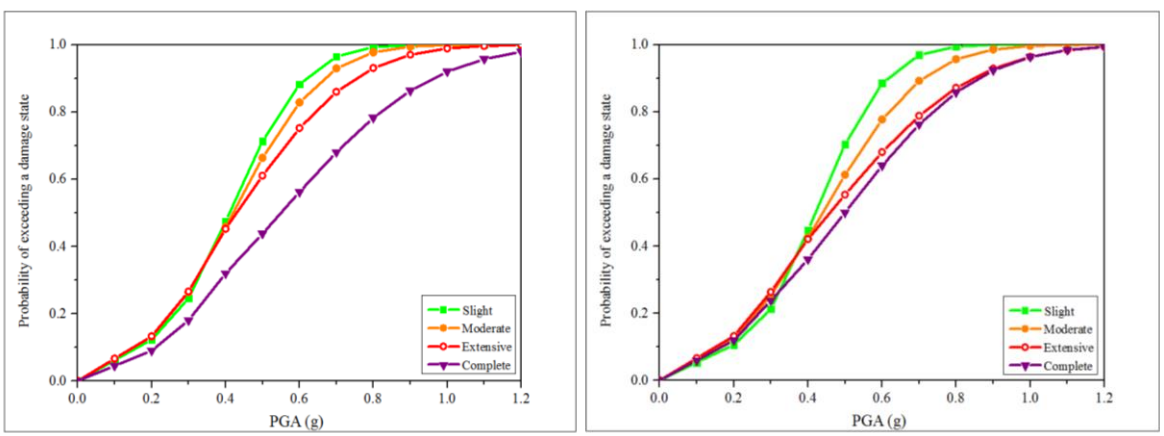
(a) *(b)*

Bridge Model 01



(a) *(b)*

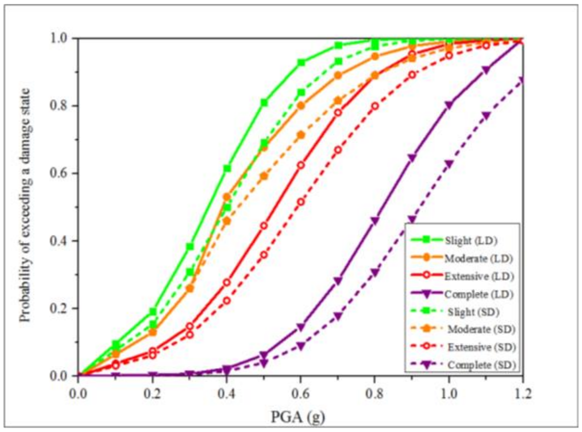
Bridge Model 02

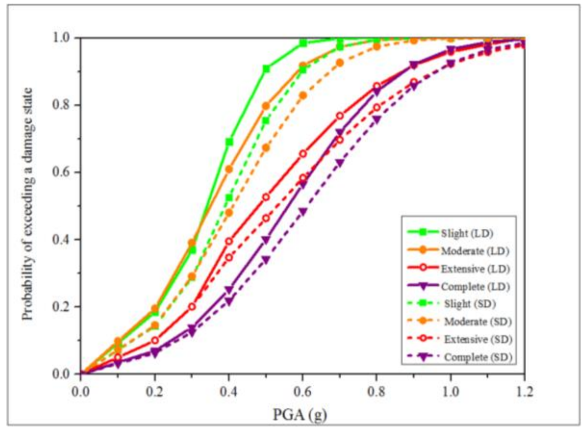


(a) *(b)*

Bridge Model 03

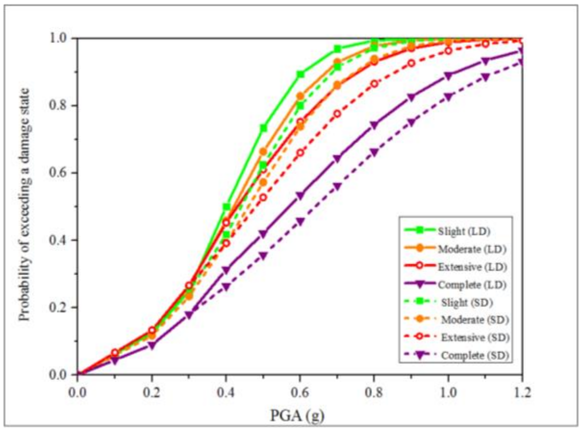
Figure 3. Seismic fragility curves for bridge models subjected to seismic intensity effect in (a) Longitudinal directions, (b) Transverse directions.

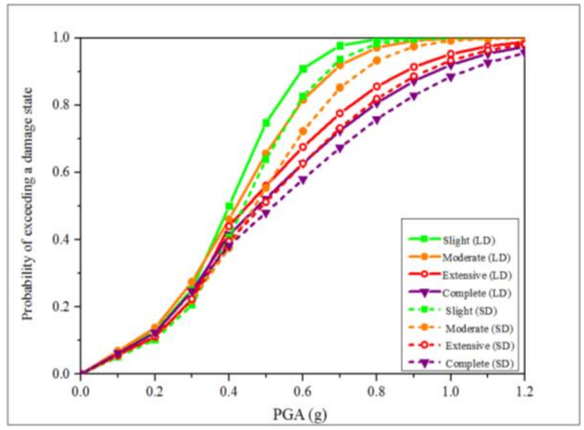




(a) *(b)*

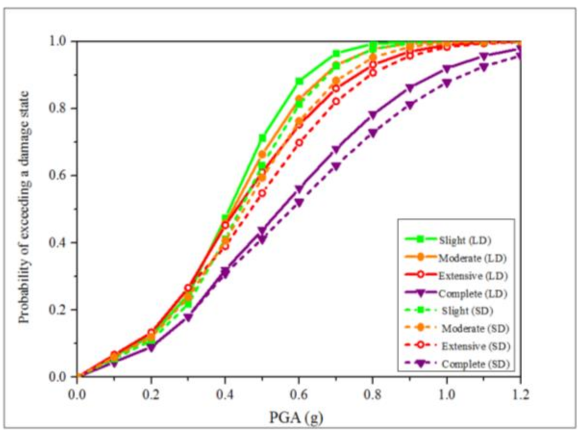
Bridge Model 01

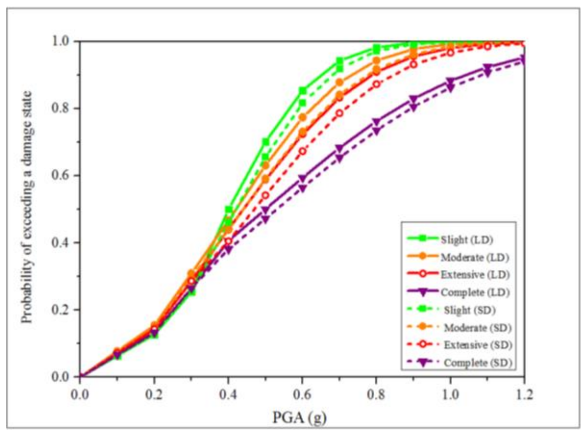




(a) *(b)*

Bridge Model 02

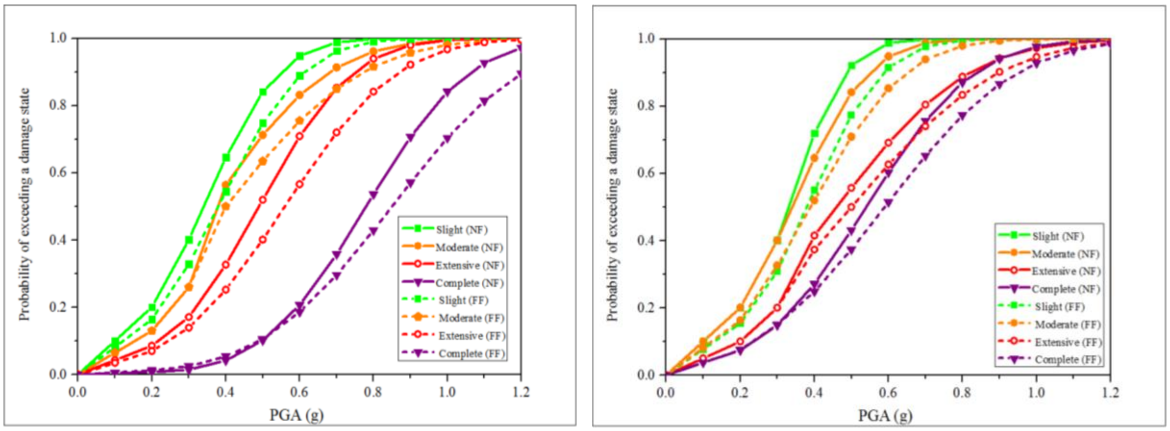




(a) *(b)*

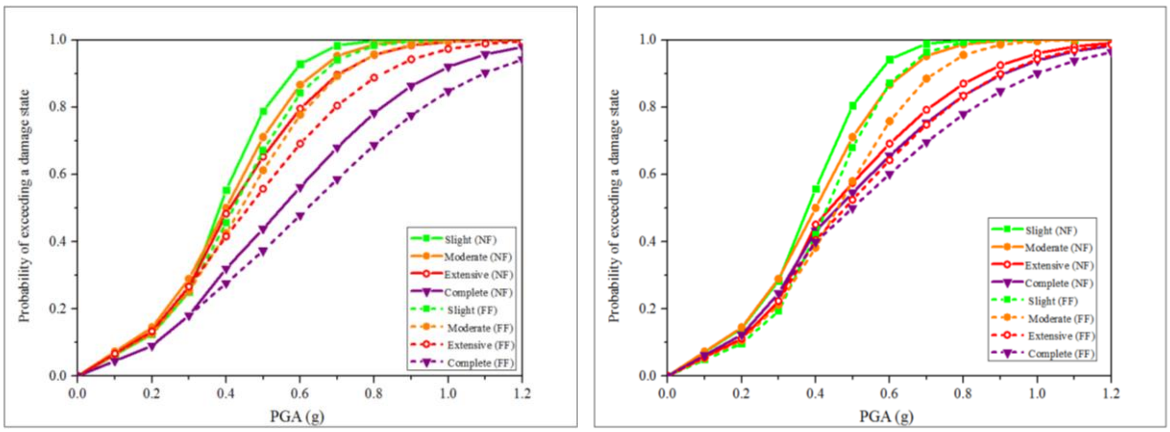
Bridge Model 03

Figure 4. Seismic fragility curves for bridge models subjected to earthquake duration effect in (a) Longitudinal directions, (b) Transverse directions.



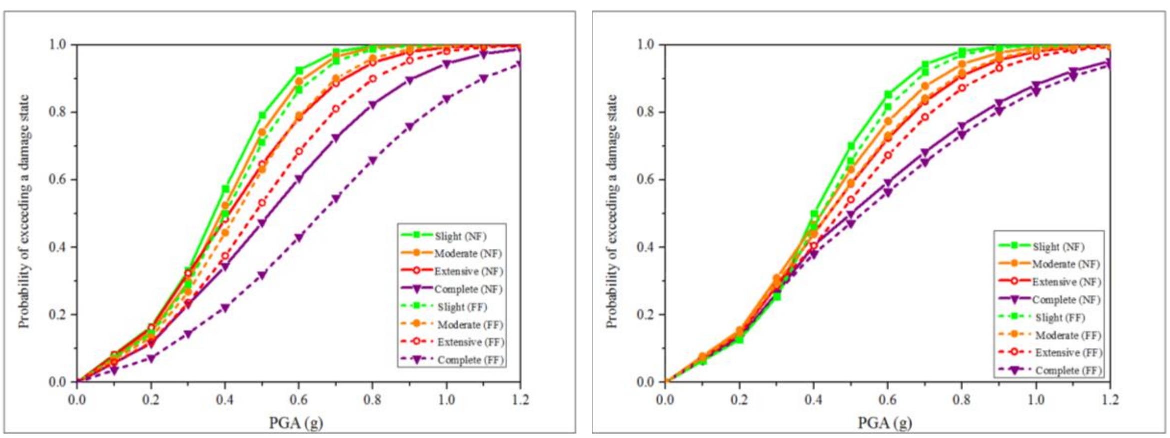
(a) *(b)*

Bridge Model 01



(a) *(b)*

Bridge Model 02



(a) *(b)*

Bridge Model 03

Figure 5: Seismic fragility curves for bridge models subjected to epicentral distance effect in (a) Longitudinal directions, (b) Transverse directions.

RESULTS DISCUSSION

Evaluation of the fragility curves offers a valuable insight into the effectiveness of various earthquake parameters on the probability of the damage considering the impact of both the bridge's demand and capacity. Figure 3 illustrates the significant effect of seismic intensity on bridge's fragility. As the seismic intensity increases, the probability of bridge damage or failure also increases. This means that the fragility curve indicating a higher probability of damage when subjected to a height seismic intensity measure.

In addition to the seismic intensity, the effect of earthquake duration and epicentral distance on the fragility of bridges are quite apparent in the fragility curves illustrated in the figures 4 and 5. For better understanding of their impact, a comparison of median values of PGA for all bridge models in longitudinal and transverse directions subjected to short and long duration as well as to near fault and far field effect was established and proved in the following figures.

As it can be observed from Figure 6 and 7, which compare the median values of PGA for short and long duration, the bridge model's fragility in both directions are comparable under the slight and moderate damage states. However, the fragility of bridges in the longitudinal direction when subjected to long duration earthquake becomes higher under the two others damage states. Whereas in the transverse direction, they are lower as compared to the longitudinal direction.

The comparison of the intensity measure median values presented in Figure 8 and 9 for bridge models subjected to epicentral distance effect in longitudinal and transverse directions respectively, can reveal a notable difference between the median values got in the extensive and complete damage state. Where the effect of near fault is significantly pronounced when compared to the far field motions. Nonetheless, in the rest damage states, the median values are equivalent.

On the other hand, this analyses indicates that near fault are the most critical parameter for the seismic damage experienced by a bridge in comparison to the far field, short and long duration motions.

CONCLUSION

In this study, a probabilistic approach was implemented for the development of the fragility curves for multi-span continuous girder bridges models. The methodology used for assessing the fragility of this bridge type includes the use of analytical attitudes based on time-history analysis to investigate the effects of earthquake ground motions parameters on bridges fragilities.

From the presented results, the main conclusions are summarized as follows:

Four damage states, namely slight, moderate, extensive, and complete, are developed for each bridge model according to the seismic intensity appropriate to each level of damage probability.

Analyses of the fragility curves reveal that the seismic vulnerability of the studied bridge type is more critical under near fault ground motion excitation, which is more destructive than the case of far field, short and long duration ground motion excitation.

Overall, the findings of this work contribute to a better understanding of the complex relationship between earthquake ground motion parameters and bridge seismic performance, and can notify the development of more effective seismic design codes and standards for bridges. The research highlights the importance of considering earthquake parameters in bridge design, assessment, and retrofitting, and emphasizes the need for further studies to investigate the effects of this parameter on other types of bridges and in different seismic regions.

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