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Indexing Seismic Fragility Curves of Skewed Reinforced Concrete Bridges

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ABSTRACT

Skewed bridges are frequently utilized in highway interchanges where straight or un-skewed bridges are impractical. Several bridges with geometric anomalies, particularly substantial skewness, have been observed to be heavily damaged. This research is a subsidiary value added to bigger research with title "seismic fragility assessment of skewed reinforced concrete bridges" [1,2] which studies seismic vulnerability analysis of skewed reinforced concrete bridges using a first-order reliability approach to calculate the failure probability effectively and precisely using a new structural reliability method that includes structural and reliability analysis (FORM). As a result, 2D seismic Curves are developed from multiple fragility curves which represent the seismic reliability of the structures but without a valid indexing method for each curve to be able to compare the curves and define each of them with an index to be used in further computational analysis. Several research have been done in the field of indexing the 2D fragility analysis curves. But there is still more research that needs to be done in indexing the 2D fragility curves and proposing a method for comparing different curves. This research will present a sufficient method for such assessment which can be used in the future for the required 2D curve quantification.

Introduction

To evaluate the effect of skewness on seismic susceptibility, this study conducts a seismic vulnerability analysis of straight and skewed reinforced concrete bridges with various skew angles and compares their seismic performances using fragility curves. Various bridge models are generated by changing the US Federal Highway Administration's (FHWA) design example No. 4 [3]. To better capture true bridge performance, detailed analytical models are used, resulting in more accurate seismic fragility curves. A new structural reliability approach is developed, and an integrated computational framework is established, which integrates structural analysis and reliability analysis tools, to handle the growing computational expense associated with the use of the detailed model. Failure probabilities are estimated analytically given seismic capacity and demand values acquired from simulations using the first-order reliability method (FORM) approach [4-6], allowing for the efficient generation of a fragility curve. Unlike prior studies, eight limit states are postulated based on the highest permissible pier drift ratio, and 2D fragility curves of the analyzed bridges are constructed, which incorporate all 2D fragility curves without a thorough indexing method to quantify each curve.

Previous research has been done in indexing the 2D fragility curves, such as [7] where an index has been developed to be used in the seismic assessment of irregular and torsional-imbalanced structures. The

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research prepares a demand-to-capacity ratios (DCRs) by analyzing the displacement demand, ultimate displacement capacity and developing a weighting parameter for the x and y direction. After developing these factors in the 2D directions, the relation between the supply and demand is assumed to be an ellipse and by intersecting the slope of the 2D plane with this ellipse, the bidirectional capacity index of the structure can be concluded. Another study has been done by [7] to indexing the 2D fragility curves using the maximum inter-story drift ratio (MIDR) which is a widely used reliable method of indexing in the 2D fragility curves. Another approach in this research area is the structure robustness indexing method which is a ratio between the damages up to unavoidable collapse state for hazard to damages up to collapse state for the same hazard as introduced by the work of [8].

Seismic Fragility Curves

Proposed Computational Models

The nonlinear finite element analysis application ZEUS-NL is used to create analytical models to simulate the structure behavior of the elements; several research have been done in the field of simulation in civil engineering such as the work of [9] which is done to simulate the construction of linear projects. Each girder and pier are made up of six and seven different parts. The hollow rectangular cross section of the reinforced concrete girders measures 1030.9 cm external width, 909.2 cm internal width, 182.9 cm external depth, and 133.1 cm internal depth. The 121.9-cm-diameter reinforced concrete piers have a circular cross section. The modeling considers the nonlinear behaviors of steel and concrete materials; for steel and concrete, the bilinear elastoplastic model with kinematic hardening and modified Mandir's model [10] are used, respectively. The pier supports are depicted as pins with limited translation movement but unlimited rotation. The abutments are modeled as translational springs on roller supports. A total of five analytical models are created. The first is the SK000, which is a straight bridge model (i.e., a 0º skew angle). The remaining four are skewed bridge models with skew angles of 15º, 30º, 45º, and 60º perpendicular to the straight bridge centerline alignment, and are designated by the letters SK015, SK030, SK045, and SK060, respectively. Table 1 lists all the analyzed analytical models' skewness angles and fundamental periods, as well as their reference names. As the skew angle grows, the first fundamental period decreases.

Table 1. Studied Analytical Models

Bridge Model	Straight Bridge	Skewed Bridge			
	SK000	SK015	SK030	SK045	SK060
Skew angles (º)	0	15	30	45	60
1st period (sec)	0.669	0.668	0.664	0.657	0.642
2nd period (sec)	0.291	0.283	0.264	0.262	0.318
3rd period (sec)	0.214	0.217	0.229	0.241	0.220

Limit State and Structural Uncertainty

Serviceability, damage control, and collapse prevention are typical limit states used in fragility analysis. The serviceability, damage control, and collapse prevention limit states in any of the bridge piers are specified in this study at the first yielding of reinforcing steel, maximum element strength, and maximum confined concrete strain, respectively. The global drift ratio is used as a damage index to determine if a bridge will fail based on the damage condition given. Pushover analyses are used to determine the pier drift ratio threshold values for each limit-state condition.

Seismic Fragility Curves

Seismic fragility curves for straight and skewed bridges with varied skew angles are driven using the integrated platform FERUM-ZEUS. The failure probability estimated from a series of structural and reliability evaluations is represented by each data point in the 2D plan. Each fragility curve is subjected to a series of regression analyses to generate a functional form for general use. Figure 1 shows the seismic fragility curves of the bridges studied at 0º and 75 º skew angles (SK000 and SK075) at 1% limit state. This graph depicts the bridge's failure probability in terms of the PGA. The generated seismic curves depict the bridge's seismic susceptibility in its entirety. As expected, the failure probability rises as the damage state is narrowed, and the skewness of the bridge causes large changes in the fragility curve.

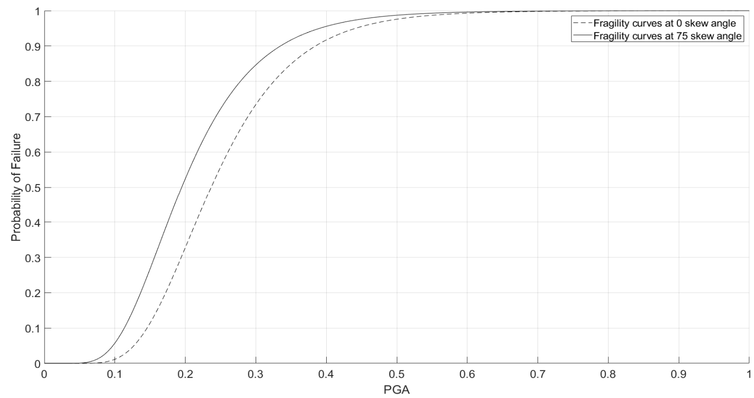

Figure 1. Seismic fragility curves of straight and skewed bridges: (a) 0º and (b) 75º.

Indexing Seismic Fragility Curves

Mathematical derivation

The Fragility curves produces from the previous analysis was found to follow a log-normal distribution (more particular a cumulative log-normal distribution, which is a continuous probability distribution of a random variable whose logarithm is normally distributed [11]. This distribution has important parameters that can be used in the derivation of our fragility index such as mean, standard deviation, median (which is the central number of a data set after arranging data points from smallest to largest and locate the center), and mode (which is the global maximum of the distribution). The proposed fragility index will be divided into two parts with equal impact of fragility on the curve, the first one will be the **Exponential Form** of the index which is derived as follows from the mode equation of the log-normal distribution.

$$Mode = e^{\mu - \alpha^2} \tag{1}$$

$$Ln(Mode) = \mu - (\alpha \times \alpha)/\mu \tag{2}$$

$$\frac{1}{\mu} \times Ln(Mode) = 1 - \left(\frac{\alpha}{\mu}\right) \times \alpha \tag{3}$$

$$Ln(Mode)^{\frac{1}{\mu}} = 1 - \beta \times \alpha \tag{4}$$

$$I_x = (Mode)^{\frac{1}{\mu}} = e^{1 - \beta \times \alpha} \tag{5}$$

Where μ is the mean value of data, α is the standard deviation of the data, β is the coefficient of variation which represents the ratio of the standard deviation to the mean, and it is a useful statistic for comparing the degree of variation from one data series to another.

The preliminary index I_x is a novel way to transforming the Fragility Curve into the exponential form which can be used for comparison with value e^1. This index main parameters are the coefficient of variation and the standard deviation where both can represent the degree of deviation of the data in the 2D plan (Scattering ratio) which is significant in avoiding the brittle failure of the structure, which means as the term $(\beta \times \alpha)$ increase, the structure becomes less fragile (less exposed to brittle failure). This will lead to the decrease of the I_x index. The term e^1 is very useful in normalizing the I_x into a value between zero and 1 as following were 1 is the least fragile and 0 is the most fragile which serves the numerical quantification purpose of the 2D curve as well as the comparative purpose:

$$I = \frac{(e^1 - I_x)}{e^1} \tag{6}$$

The second part of the index will be the **Amplification factor** which is the linear portion of the curve experiencing the zero probability of failure before the start of the failure zone as shown in figure 2, this part is very important because most of the structure will be exposed to this portion through their whole life cycle without any seismic hazard occurrence.

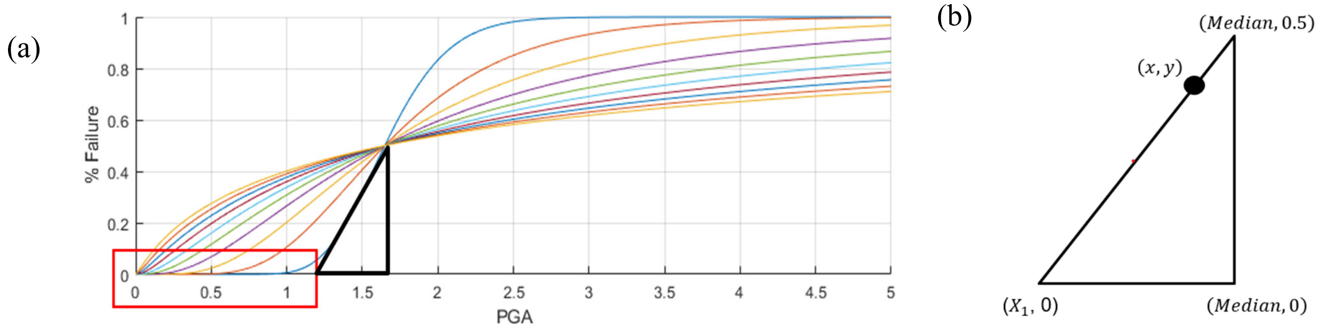

Figure 2. Amplification factor presentation and derivation

Through analyzing the triangle's boundaries derived in figure 2, the amplification factor is presented as following in equation 7, a value between 0 and 1 where 0 is the most fragile and 1 is the least fragile. The final fragility index is the multiplication of the Exponential form Index and the Amplification factor as shown in equation 8 which is a value between 0 (most fragile) and 1 (least fragile).

$$A_f = \frac{X_1}{Median} \tag{7}$$

$$I_f = A_f \times I \tag{8}$$

The proposed index was applied to the studied skew bridge cases at different angles as shown in table 2; the results show that as the skewness angle increase the deviation of data also increase which makes the structure less fragile, however, the amplification factor will decrease dramatically which makes the structure much more fragile (the amplification factor became the dominant factor). As a result, the overall fragility index will decrease as the skewness angle increase making the structure more fragile as anticipated. These results show the advantages of this index in the numerical quantification and the comparative objectives.

Table 2. I_F Index results for different skew cases (Using volume under the curve approach)

	Straight Bridge	Skewed Bridge				
	SK000	SK015	SK030	SK045	SK060	SK075
Skew angles (º)	0	15	30	45	60	75
I	0.4307	0.4125	0.4778	0.4822	0.5329	0.5670
A_f	0.4762	0.4364	0.3750	0.3590	0.3158	0.2973
I_f	0.2051	0.1912	0.1792	0.1731	0.1683	0.1686

Conclusions

The generated fragility curves show that the skew angle has a direct impact on the bridge's seismic susceptibility. The vulnerability analysis clearly reveals that as the skew angle grows, skewed reinforced concrete bridges become more sensitive to seismic damage. For general usage in skew bridge design, this study gives useful forms of seismic fragility curves with varied skew angles. From the above represented results, it can be concluded that the skewness angle has significant effect on the structure resistance to seismic load; as the skewness angle increase, the proposed If index decrease reflecting more tolerance to failure. Finally, this research presented a new approach for quantifying Index for fragility curves and comparing them which can be significantly useful in future computational and analytical applications.

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