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Research on seismic fragility of the isolated girder bridge base on performance under near-fault ground motions

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Abstract. The seismic fragility of a RC isolated continuous girder bridge is analyzed as a case, and the damage of bridge piers and isolated bearing components is considered. Meanwile, the incremental dynamic analysis of the bridge structure under different failure conditions is carried out, the randomness of the near ground motion and the structural parameters are taken into account. Based on the damage index of isolated bridge under different damage conditions, the seismic fragility curves of each member and the whole bridge structure of the isolated bridge are obtained according to the ability and the demand of the structure. The research shows that the safety control of the isolated continuous beam bridge structure is mainly affected by the seismic vulnerability of the isolated bearing, and the influence of bridge pier seismic fragility is relatively small. By applying the isolation scheme, the probability of the bridge structure with different damage state is greatly reduced, thus the seismic performance is improved. The results will provide a reference for future seismic damage prediction.

Keywords. RC isolated continuous girder bridge, near-fault ground motions, seismic fragility analysis, damage index, isolated bearing.

1. Introduction

The bridge structure is an important hub of transportation systems, especially in reinforced concrete long span continuous girder bridge, most widely applied in highway in our country. All previous earthquake disaster statistics show that these bridges will cause serious damage to the earthquake. In order to effectively reduce the seismic damage of bridges, the isolation design of lead rubber bearing (LRB) is used in the actual engineering. The seismic responses of such isolated structures have already been widely investigated [1-3]. The studies show that this structure can adapt to different working conditions, further, it can effectively reduce the seismic effect of bridge pier under rare earthquake. However, under the near fault ground motion with strong non stationary feature, this kind of isolated bridge may have adverse effects on the seismic performance and design of the isolated bridge, such as, displacement of the supporting seat, the expansion joint, and the pier beam, and even the collision of the main beam will result to seismic damages of beam falling-off. What is more, the large bearing displacement and the isolation device failure can create a serious damage to the structure [4-5].

In this paper, taking a RC isolated continuous girder bridge as a case, the probabilistic seismic demand and seismic capacity are analyzed on the bridge components and structure system, based on the probability analysis of seismic performance, then results of seismic fragility analysis of bridge structures are obtained. A basis is presented as a guide for structural seismic design, reinforcement and maintenance decision making, etc.

2. Seismic fragility analysis method and definition of seismic damage

2.1. Seismic fragility analysis method

Structural seismic fragility is a probability, that the structural damage exceeds a specified value when the ground motion intensity reaches a certain value. The seismic fragility of bridges can be expressed as:

$$F_R(a) = P[EDP \geq LS \,|\, IM = a] = \int_V^{\infty} f_{R|IM}[r|a]dr \tag{1}$$

Where, $F_R(a)$ is seismic fragility, P is the probability of the structure failure exceeding a specified value, EDP is engineering demand parameter, LS is state limit of structure, IM is the intensity coefficient of ground motion; $f_{R|IM}\left[r \mid a\right]$ means that, when the ground motion intensity is a IM, the structure (component) of a certain engineering demand parameter (EDP) reaches or exceeds the conditional probability density of a specified damage state.

Assuming that the relationship between EDP and IM follows the log normal distribution, the mean value of the structure (or component) is:

$$\overset{\wedge}{EDP} = b(IM)^c \tag{2}$$

Where, C and B are correlation coefficients.

The seismic fragility of structural limit state can be calculated. And the smooth "seismic fragility curve" is obtained by statistical curve fitting:

$$P = [EDP \geq LS \,|\, IM] = 1 - \Phi\left(\frac{\ln(LS_m - \ln(bIM^C)}{\sqrt{\beta_{LS}^2 + \beta_{EDP}^2}}\right) \tag{3}$$

Where, Φ is cumulative density function of standard normal distribution, L_{Sm} is log normal distribution under structural damage states, β_{LS} is log standard deviation of structural capacity, β_{EPD} is log standard deviation of structural requirements.

2.2. Definition of seismic damage of isolated continuous girder bridges

The level of seismic performance of structures is a finite state of damage and the damage of structures should be related to the level of performance [6]. Bridge structure damage under earthquake is mainly the damage of bridge pier, bearing and main beam component, especially the bridge pier is the most easily damaged component. In this paper, the damage state of the bridge is defined in two aspects, such as the failure of the bridge piers, the failure of the isolated bearing, and thus the corresponding damage index is determined.

2.2.1. Bridge pier

With the curvature of piers as engineering demand parameters (EDP), and with the curvature ductility ratio μ as damage index, the damage index of bridge piers can be determined by the moment curvature relationship of the section of different damage conditions [7]. Earthquake damages show that the bottom of the bridge pier under earthquake is the first failure. So the damag state is defined by the curvature of the bottom section of the bridge pier, and the damage state and damage index are described at all levels, as shown in Table 1.

Table 1 Damage Status and Description of Damage Index for Piers

Damage state	Basically intact	Minor damage	Medium damage	Serious damage	Collapse
Failure criterion	$\phi \le \phi_y^{/}$	$\phi_y^{/} \le \phi \le \phi_y$	$\phi_y \le \phi \le \phi_d$	$\phi_d \le \phi \le \phi_u$	$\phi \ge \phi_u$

Note: $\phi^{/}_{y}$ is that the first reinforcement yielding, concrete cracking; ϕ_y is that the plastic hinge of the section appears; ϕ_d is the maximum value of the bending capacity; ϕ_u is the limit bending state.

2.2.2. Isolation bearing

The failure state of the isolated bearing is mainly determined by the displacement and shear strain of the bearing. Five damage states, including basically intact, minor damage, moderate damage, severe damage, and collapse, are defined by Choi according to the displacement of the bearings. Here, displacement of isolated bearing based on bearing shear strain is adopted as a basis for the evaluation of earthquake damage. And the definition of the deformation rate of the bearing under different damage states is given in Table 2.

Table 2. Description of Isolated Bearing Damage Indexes（unit: mm）

State	No damage	Minor damage	Moderate damage	Severe damage	collapse
Index	$d_\Delta \le 100\%\gamma$	$d_\Delta \le 150\%\gamma$	$d_\Delta \le 200\%\gamma$	$d_\Delta \le 250\%\gamma$	$d_\Delta > 250\%\gamma$

Note: d_Δ is relative horizontal displacement, γ is the total thickness of the rubber layer.

3. Model of isolated bridge and random simulation of seismic isolation structure

3.1. Model of isolated bridge structure

The study object of this article is a six span reinforced concrete continuous girder bridge, and the total length is 120m. The bridge arrangement is shown in Figure 1. The bridge superstructure is 6×20m cast in place concrete box girder with beam height of 1.3m and concrete of C40. The lower part of the structure is RC circular pier column with C30 concrete. No.1 and No.5 piers are double column piers with 1.3m in diamenter and 8m in height, No.2, 3, and 4 piers are variable cross-section one-column circular bridge piers with height of 8m and diameter of 1.5m piers. The main girder and the pier top are connected by LRB500 isolation bearing by setting expansion joints on both sides of the stage. The bridge pier foundation material is C30 concrete. The seismic fortification intensity is 8 degrees in the area, and the site class is II.

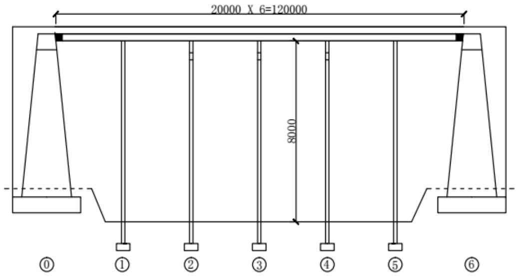


Figure 1. The isolated girder bridge structural configuration

The finite element dynamic analysis model of bridge structure is established by using OpenSees software, and the seismic response of the structure is only considered input of longitudinal seismic motion.

3.2. Selection of near field seismic records

The object of this paper is to choose near fault ground motion. It is very important for the accuracy and efficiency of structural fragility analysis to select the reasonable seismic wave classification and the appropriate number of seismic waves. The wave should meet two requirements, the first is to be able to simulate the random process of earthquake disaster itself, and the second is that a large number of adequate seismic waves should be selected to reduce the impact of ground motion uncertainty on the results of vulnerability analysis. In the present study, a new generation seismic record database in the Pacific Earthquake Engineering Research (PEER) center are used as reference. According to the structure of the site conditions and magnitude, 100 near field seismic records with a fault distance less than 20km and with significant velocity pulse effect is selected. The basic characteristics are: (1) variation range of near fault distance: 0-20 km, (2) Magnitude variation range: 6.5-7.6, (3) v_{s30} range: 260-510m/s, and (4) there are obvious pulse velocity.

3.3. Stochastic simulation of ground motion and isolated bridge structure

The curvature ductility of the pier bottom and the displacement of the isolation bearing are selected as evaluation indexes. the parameters of each group are altered. In order to eliminate the difference of the structural analysis of each uncertainty parameter, the data were normalized, and the sensitivity results of the structural parameters of PGA (1.0g) seismic action were obtained. The analysis shows that yield strength of steel, quality of the upper structure, compressive strength of concrete, pre-yield stiffness of bearing (K_1), and yield shear of bearing (Q_y) are sensitive to the seismic response of bridge structures. The structure parameters of sensitive variable probability distribution statistics are shown in Table 3. Then the Latin hypercube sampling method (LHS) is applied to create ten analysis samples of the bridge structure with random combination of five main parameters. Finally, a combination of the 10 samples and the selected 100 near field seismic wave records are combined to generate a large number of random isolated bridge structures.

Table 3. Statistics of the Random Variable

random variable	probability distribution	average valu	standard deviation	unit
Yield strength of steel	normal distribution	385.42	28.32	MP
Compressive strength of concrete	normal distribution	27.68	5.23	MP
Quality of upper structure	normal distribution	28930	2530	N/m3
Pre yield stiffness of bearing	uniform distribution	12357	16573	KN/m
Yield shear of bearing	uniform distribution	54.83	73.86	KN

4. Seismic fragility analysis of isolated bridge system

4.1. Seismic fragility analysis of isolated bridge members

As an example, only No.3 pier is provide based on the damage index. The isolated bearing of the fragility curves under different damage conditions are plotted in Figure 2 and Figure 3, respectively.

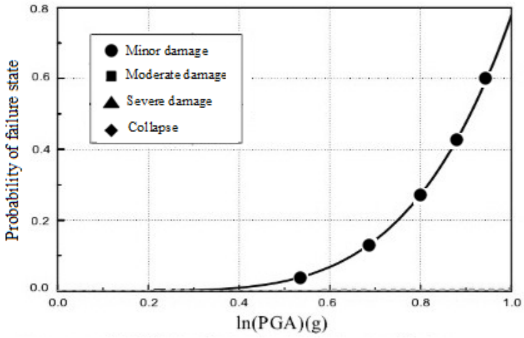


Figure 2. Fragility curves of pier

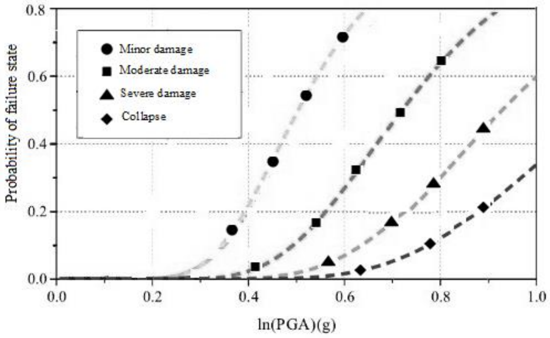


Figure 3. Fragility curves of isolated bearing

As is shown in Figure 2, No.3 pier with isolated bridges remains intact under frequent earthquake action (PGA=0.11g). In the case of rare earthquake (PGA=0.51g), the probability of a minor damage to the bridge pier is 4%, but without moderate damage, severe damage, complete destruction or other incidents. No minor damage happens in the frequent earthquake and only small probability occurs under the rare earthquake, it is because that the pier can bear a greater force, which reflects the demand of ductility design of bridge components. It shows that the seismic demand of bridge pier is greatly reduced in the isolation bearing structure.

As can be seen from Figure 3, under frequent earthquake action (PGA=0.11g), isolated bearing is not easy to damage. However, under the rare earthquake action (PGA=0.51g), the the damage of bearing occurs, the probability of minor, moderate and severe damage is 52%, 11%, and 4%, respectively, but the collapse of the isolated bearing does not happen. Compared with the bridge pier, the seismic fragility of isolated bearing plays a key role in the safety control of isolated continuous girder bridge. This is mainly because of the isolated continuous girder bridge cancelling the braking pier, the deformation of the isolated bearing is relatively large, so that the seismic fragility of the isolated bearing is large.

4.2. Seismic fragility analysis of isolated bridge structure system

Isolated bridge structure is a series system which is composed of all the structural members of the bridge, and for the multi spans isolated continuous girder bridge, the correlation between the failure modes of structures under various damage conditions is considered. Therefore, the reliability theory is applied to consider the relationship between failure modes of the two main damage states, and to estimate the failure probability interval:

$$P(F_1)+[P(F_2)-P(F_1\cap F_2)]^+ \le P_{sys} \le P(F_1)+P(F_2)-[P(F_1\cap F_2]^+ \quad (4)$$

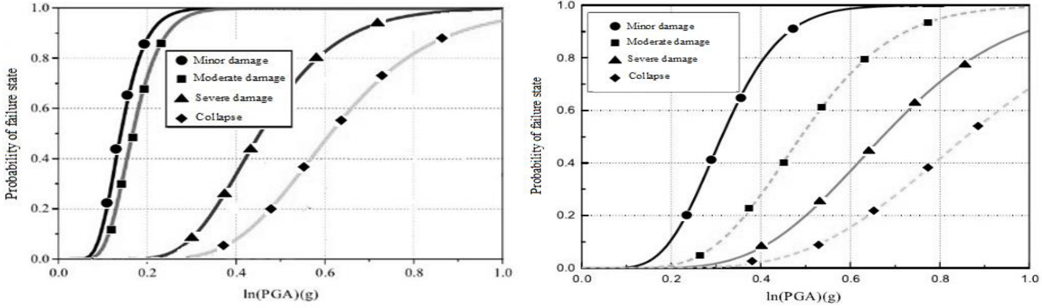
Where, $P(F_1)$、$P(F_2)$ respectively indicates the failure probability of first and 2 damage states. P_{sys} is failure probability of each damage state; $[\ ]^+ = \max(,0)$, $P(F_1\cap F_2)$ is the transcendental probability of the failure mode of the structure under two kinds of damage state.

The failure probability of the isolated bridge structure system is calculated:

$$P_{sys} = P(F_1)+P(F_2)-P(F_1\cap F_2) \quad (5)$$

In order to compare the seismic isolation effect of the seismic isolation system, the fragility curves of the general bridge and isolated bridge are given, as is shown in figure 4.

As can be seen from the figure 4, under frequent earthquake action (PGA=0.11g), the probability of minor damage and moderate damage of general bridge are 18% and 6%, respectively. but the isolated bridge remains basically intact. Under rare earthquake action (PGA=0.51g), the probability of serious damage of general bridge is 68%, and the probability of collapse is 29%, but the probability of minor damage, moderate damage, severe damage and collapse of isolated bridges are 92%, 56%, 20%, and 10%, respectively. Therefore, the probability of the bridge structure with different damage states is greatly reduced after the seismic isolation scheme.



(a) General bridge (b) Isolated bridge

Figure 4 Compare fragility curves of isolated bridge with general bridge

5. Conclusion

The isolation of common span reinforced concrete continuous girder bridge is selected as a research object, Meanwile, the randomness of ground motion and structural parameters of the bridge structure under stochastic incremental dynamic analysis of different damage conditions are taken into account. Therefore,It can be more reasonable to evaluate the seismic performance of the isolated structure. The main conclusions are as follows:

(1) In the seismic fragility analysis of isolated continuous girder bridges, the failure probability of the isolated bearing is relatively large. Limit state failure is more likely to occur, and the failure probability of the pier is small. Therefore, in the seismic design of this kind of isolated bridge structure, seismic isolation bearing capacity should be taken into consideration.

(2) The probability of failure of the seismic fragility of isolated bridge structure system is greater than that of the seismic fragility of bridge structural members. At the same time, the bridge structure is greatly reduced in the failure probability of various damage states using seismic isolation scheme. The seismic isolation scheme can greatly improve the seismic performance of the bridge.

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