Seismic Vulnerability Analysis of Isolation Bearing for Curved Continuous Girder Bridge

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Abstract. Based on a curved continuous girder bridge project, this thesis employed the seismic vulnerability method to analyze the isolation bearings which were usually considered as the fragile member of bridge. Laminates rubber bearing (LNB) was selected for analysis. The mechanical model and damage index are determined. The vulnerability curve of the bearings could be formed with the traditional reliability method based on logarithm linear regression analysis. Determined the mechanical model and damage index of the bearing, and the nonlinear dynamic analysis model of the bridge is established. Selected ten records of earthquake and amplitude modulated according to the requirements of incremental dynamic analysis method. Then, respectively formed the bridge - ground motion random sample with the bridge random sample. The analysis results indicated that the position of isolation bearings and the direction of seismic inputting had different level effect on damage probability of bearings.

Keywords. Curved continuous girder bridge, vulnerability, damage index, isolation bearing.

1. Introduction
Rubber bearing is the most widely used support in continuous beam bridge, and it can play the role of isolation and shock absorption. However, due to its own geometric irregularities, curved continuous beam bridges often work under complex forces situation, such as obvious bend-and-torsion coupling of the main beam, making the bearings often become the most vulnerable members during the earthquake [1-2].

Some domestic and foreign scholars used the vulnerability curve to study the bearing damage characteristics of linear bridges [3-5], but so far there are few vulnerability research for curved girder and its bearing. In order to further understand the curved continuous bridge bearing seismic damage problem, based on the theory of vulnerability analysis, this paper take a curved continuous girder bridge project as engineering background, establishing a nonlinear dynamic analysis model, studied damage state of curved bridge bearing.

2. Mechanical Model of Bearing and Damage Index
The commonly used isolation bearings are lead rubber bearings, basin type rubber bearings, PTFE sliding plate bearings, etc. In this paper, the most common bearing: laminates rubber bearings (LNB) are used on the bridge.

2.1. Mechanical Model of Bearing
The thin steel plate inside the laminates rubber bearing can effectively restrain the lateral deformation of the rubber and greatly improve the vertical stiffness of the bearing, but it does not affect the shear deformation stiffness of the rubber layer. Laminates rubber bearings can be simulated by using linear
spring elements, and their shear stiffness $K_h$ and vertical stiffness $K_v$ are calculated according to the following equation:

$$K_h = \frac{G_d A_r}{\sum t} \quad K_v = E_{cv} \frac{A_c}{\sum t}$$

where, $E_{cv} = \frac{E_c E_v}{E_c + E_v}; \quad E_c = E(1 + 2kS_1^2)$; $G_d$ is the dynamic shear modulus of laminates rubber bearing (KN/m²); $A_r$ is the shear area of the rubber bearing (M²); $\sum t$ is the total thickness of rubber layer (m); $E_{cv}$ is the modified compression elastic modulus of laminated rubber pad; $E_v$ is the volume-constrained elastic modulus of rubber material; $E_c$ is the compression modulus of laminated rubber pad; $E$ is the standard elastic modulus of rubber material; $k$ is the hardness correction factor of rubber material; $S_1$ is the first shape coefficient of the laminated rubber pad.

In this paper, the size of laminates rubber is GYZ700×95, taking 1200 KN/m² as $G_d$; $E_v$ off for 2160 Mpa; $E$ is set as 4.54 Mpa; $S_1$ take 10.97. After calculation, the vertical stiffness of laminates rubber bearing is $v = 2.16 \times 10^9 N/m$, $K_h = 4.86 \times 10^6 N/m$.

2.2. Bearing Damage Index

For laminates rubber bearing, the relative displacement ductility ratio $\mu_x$ can be used to define the damage state of the bearing, that is, the ratio of the relative displacement of the bridge bearing under each limit state to the relative displacement $u_1$ of the bearing when the shear strain is equal to 100% is defined as the relative displacement ductility ratio of the bearing. The calculation formula of shear strain $\gamma_a$ is as follows:

$$\gamma_a = \frac{u}{\sum t} = \frac{u}{u_1}$$

where, $\sum t$ is the total thickness of rubber layer. In Code for Seismic Design of Urban Bridges (CJJ 166-2011), it is clearly stipulated that the thickness of slab rubber bearing shall be checked to meet the following requirements: $\sum t \geq \frac{X_E \tan \gamma}{\tan \gamma}$, $X_E$ is the bearing displacement after considering the combination of earthquake action, uniform temperature action and permanent action; $\tan \gamma$ is the tangent value of the shear angle of rubber sheet; $\tan \gamma = 1$

$\mu_1$ is the relative displacement ductility ratio when the shear strain of the bearing is equal to 100%. Take $\mu_1 = 1.0$ by definition, and respectively take $\mu_x = \frac{u_x}{u_1}$ as the relative displacement ductility ratio when the shear strain of the bearing is equal to 150%, 200% and 250% [6]. According to equation (2), it can be calculated that $u_x = 1.5 \mu_x = 2.0 \mu_x = 2.5$, the failure state of the bearing which is defined according to the relative displacement ductility ratio is as shown in table 1.

| Damage state       | State description                             | Damage index |
|--------------------|-----------------------------------------------|--------------|
| No damage          | The relative displacement of bearing is small and the shear strain is less than 100% | $\mu_x \leq 1.0$ |
| Slightly damaged   | The relative displacement of bearing is large, but the shear strain is less than 150% | $1.0 < \mu_x \leq 1.5$ |
| Medium damaged     | The relative displacement of bearing is large and the shear strain is less than 200% | $1.5 < \mu_x \leq 2.0$ |
| Serious damaged    | The relative displacement of bearing is very large and the shear strain is less than 250% | $2.0 < \mu_x \leq 2.5$ |
| Completely destroyed | Bearing failure, shear strain greater than 250% | $\mu_x > 2.5$ |

3. Vulnerability Analysis Method

Vulnerability analysis refers to the probability of varying degree failure of structural components or systems under different levels of ground motion [7-8]. Using the capability parameters of the structure directly, seismic vulnerability can be expressed as:
where, $IM$ is selected ground motion parameters (such as PGA, SA, etc.); $C_i$ is the capacity of the structure or component, specifically refers to the limit state between different failure states; $D$ is a requirement for a structure or component.

The distribution of demand probability and the probability distribution of the capability of the structure under the action of earthquake can be expressed by the logarithmic normal distribution:

$$
\mu_d = \ln(\bar{\mu}_d, \beta_d) \\
\mu_c = \ln(\bar{\mu}_c, \beta_c)
$$

where, $\bar{\mu}_d$ is the average value that structural demand under earthquake action, $\beta_d$ is the logarithmic standard deviation that structural demand, $\bar{\mu}_c$ is the average value of structural capacity, and $\beta_c$ is the logarithmic standard deviation of structural capacity.

The relationship between the mean value $\bar{\mu}_d$ that structural demand and ground motion parameters $IM$ is as follows:

$$
\ln(\bar{\mu}_d) = \ln(a) + b \ln(IM) = A + B \ln(IM)
$$

Using traditional reliability theory to establish the probability function of structural demand $\mu_d$ exceeding structural capacity $\mu_c$:

$$
P_f = \Phi\left[\frac{\ln(a(IM)^{b/\mu_c})}{\sqrt{\beta_c^2 + \beta_d^2}}\right]
$$

Finally, under the action of various horizontal ground motions, take the exceeding probability under different failure states to obtain the vulnerability curve of the structure.

4. Profile and Model Establishment of Curved Beam Bridges

4.1. Bridge Overview

The bridge model is based on the Jinjiang Interchange on Lipan Highway, a curved bridge with a curvature radius of 50 m. The bearing adopts rectangular laminates rubber bearing. The internal bearing is set as a fixed bearing at 11# pier, while the external bearing is set as a movable bearing that can only move radially. For the rest piers, the internal bearing is set as tangentially movable bearing, while the external bearing is set as bidirectional movable bearing that can move both radially and tangentially. The specific layout is shown in figure 1. And the specific section size is shown in figure 2.

4.2. Finite Element Model

Finite element analysis software SAP was used in this paper to build a finite element model for bridges. The main girder is modeled by elastic shell element. The middle sections of cap beams and double piers are modeled by spatial elastic-plastic beam-column elements [9]. For the plastic hinge may appear at bottom and top of pier columns, use multi-section plastic joint elements to model. The
laminates rubber bearing is modeled by linear connecting unit, the element parameters are calculated in section 1.1, and the calculation model is shown in figure 3.

### 4.3. Selection of Seismic Waves

10 seismic records were selected in this paper as the ground motion input and the incremental dynamic method is adopted for seismic demand analysis [9]. The acceleration response spectrum is shown in figure 4. Therefore, the PGA of the 10 selected seismic waves is adjusted in proportion to 0.1 g~1.0 g, with 10 levels for each 0.1 g, and 100 ground motion inputs are obtained.

Through analysis, it is found that the ground vibration input along the connecting line direction of 9 #-10# pier is an unfavorable direction. Therefore, the earthquake acceleration is input along the connecting line direction of 9 #-10# pier to analyze the seismic response of bridge.

### 5. Analysis of Bearing Vulnerability

#### 5.1. Generate Vulnerability Curve

Consider each pier being laminates rubber bearing, in order to get the relationship between relative displacement ductility ratio and peak ground acceleration (PGA), take 10 # pier bearing for example, respectively take earthquake responses of the internal and external bearing relative displacement ductility ratio and the corresponding PGA data points for logarithm linear regression analysis.

Then the seismic deformation ductility demand of the bearing can be expressed by the following equation:

\[
\begin{align*}
\text{Internal bearing: } & n(d_{d}) = 1.1723 \ln(PGA) + 1.3846 \\
\text{External bearing: } & n(d_{d}) = 1.124 \ln(PGA) + 1.4134
\end{align*}
\]

Accordingly, the probability distribution of bearing shear deformation capacity can also be expressed by a logarithmic normal distribution function:

\[
\mu_{c} = \ln(\bar{\mu}_{c}, \beta_{c})
\]

\( \bar{\mu}_{c} \) is the average value of shear deformation capacity, is represented by the damage index corresponding to each damage state of the bearing as determined in table 1.

By substituting equations (8-9) into equation (7), the failure probability (exceeding probability) of the internal and external bearings of 10 #pier under different damage states can be obtained:

\[
\begin{align*}
\text{Internal bearing: } & P_{f} = \Phi \left[ \frac{\ln(3.9932(PGA)^{1.1723}/\mu_{c})}{\sqrt{\beta_{d}^{2}+\beta_{c}^{2}}} \right] \\
\text{External bearing: } & P_{f} = \Phi \left[ \frac{\ln(4.11(PGA)^{1.124}/\mu_{c})}{\sqrt{\beta_{d}^{2}+\beta_{c}^{2}}} \right]
\end{align*}
\]
When the vulnerability curve takes PGA as its independent variable, $\sqrt{\beta_d^2 + \beta_e^2}$ is set as 0.5 [10]. Then the probability of the structural response exceeds different failure states can be calculated when the PGA of the ground motions is 0.1 g, 0.2 g, 0.3 g...to 1.0 g.

5.2. Vulnerability Analysis of Bearing

According to the data obtained from the upper section, the vulnerability curve of 10#internal and external pier bearing can be drawn as shown in figure 5. Similarly, the vulnerability curve of other pier bearings can be obtained.

It can be seen from figure 5 that the exceeding probability of the bearing under different damage states increases with the increase of peak ground acceleration (PGA). For the internal and external bearings located on the same cap beam, the exceeding probability of the external bearings is slightly higher than that of the internal bearings in the same damage state. Due to the different vertical load on the inside and outside of the girder, the bridge girder experienced torsional force, and the external bearing was subjected to more force than the internal bearing.

![Figure 5. Fragility curves of piers’ bearings.](image)

Figure 6 shows the comparison diagram of vulnerability curve under different failure states of each pier’s external bearing: under four failure states, the damage probability of the external bearing of 10# pier and 12#pier are obviously greater than that of 9 #pier and 13# pier. The displacement demand of bearings of 10#pier and 12#pier is larger. When the peak ground acceleration (PGA)=0.5 g, the probability of complete failure reaches 30% and 10%, respectively. However, when PGA<0.5 g, the bearing of 9#pier and 13#pier would not be seriously damaged. Even when PGA=1.0 g, the probability of complete failure would not exceed 10%.
The analysis results show that the failure of bearing of curved continuous beam bridge is not only affected by the position of bearing, but also by the input direction of ground motion. In addition, it can be seen that: the bearing position has a greater influence, the internal bearing piers are more easily to be damaged than the side pier bearing. For example, the 9 # pier is the side pier and 12 # pier is the internal pier, while the 9 # pier bearing has smaller angle between tangential sliding direction and the ground motion input direction, but vulnerability curve shows that the 12#pier bearing experience severer damage. The 9# and 12# bearing has the same specifications, that means they have the same shear stiffness. In contrast, the displacement demand of the 9# bearing is relatively small, so the 9#pier has the lower failure probability.

6. Conclusion

Take Taojiadu interchange bridge of Lijiang (Panzhihua) expressway as the example, this paper established the finite element model, and use the traditional reliability probability analysis method to analyze the vulnerability of the curved girder bridge. The main conclusions are as follows:

1) The exceeding probability of the bearing of curved continuous girder bridge will increase with increasement of the ground motion: For the double-column piers, the exceeding probability of the external bearing is higher than that of the internal bearing on the same pier. It shows that the vertical loads on the internal and external bearings are different greatly due to the bending-torsion coupling effect of curved girder bridge, and the external bearings are subjected to greater forces than the internal bearings. The external bearings are more likely to be damaged, so we should pay attention to the design of the external bearings.

2) The failure of isolation bearing is related to the input direction of ground motion. Under different input directions of ground motion, those which has the smaller angle between the tangential...
sliding direction (shear deformation) of the bearing and the input direction of ground motion might have greater damage probability.

3) The damage probability of each pier bearing of the curved continuous girder bridge is related to the position of the pier. The pier bearings in the middle of the curved bridge are more likely to be damaged than those at the side pier. The reason is that the middle pier bearings bear larger load transferred from the upper part. And the displacement demand of the side pier bearing is relatively small, so the failure probability of the side bearing is smaller. Therefore, the design of the bearing at different pier of the curved bridge should be optimized considering the location of the pier.

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Reference

[1] Xie X 2008 Seismic response analysis and Seismic design of bridge structures.
[2] Lei J Q and Song L X 2012 Earthquake damage analysis and seismic performance research of Wenchuan Baihua Bridge Journal of Beijing Jiaotong University 36(1) 1-5.
[3] Chen L B, et al. 2018 Seismic vulnerability model and simplified calculation method for highway rule beam bridges Journal of Southwest Jiaotong University 53(1) 146-155.
[4] Li Li F, et al. 2011 Seismic vulnerability analysis of slab rubber bearings Journal of Hunan University: Natural Science 38(11) 1-6.
[5] Osman O M, Ramadan, et al. 2020 Assessment of seismic vulnerability of continuous bridges considering earth-structure interaction and wave passage effects Engineering Structures 206.
[6] Zhang J R, et al. 2003 Structural reliability theory and its application in bridge engineering.
[7] Li L F, et al. 2012 Evaluation of seismic performance of bridges with high piers and long spans based on IDA Earthquake Engineering and Engineering Vibration 32(1) 68-77.
[8] Xu Y Q and Liu J W 2008 Analysis of elastic-plastic mechanical behavior of concrete curved beams Acta Railway Sinica 30(003) 83-86.
[9] Chen L, et al. 2015 Practical seismic wave optimization selection method considering duration in performance-based seismic design of bridges Vibration and Impact 34(3) 35-42.
[10] Hwang H and Liu J B 2004 Vulnerability analysis of reinforced concrete bridge structures under earthquake action Journal of Civil Engineering 37(6) 47-51.