Seismic Vulnerability Analysis of Double-column High-pier Rigid Frame Bridge with Tie-beams Subjected to Near-fault Earthquake Inputs

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Abstract. Due to short duration and high energy characteristics, near-fault earthquakes showed more destructive damage on bridges. For double-column high-pier rigid frame bridges, tie-beams between double-columns play an important role in seismic resistance. Therefore, the influence of traditional reinforced concrete tie-beams and energy dissipation braces on the seismic performance of high-pier rigid frame bridges under near-fault earthquakes were analyzed based on the seismic vulnerability analysis. It was showed that as the number of tie beams increases, the plastic hinge curvature on the top and bottom of the pier gradually decreases, and the probability of exceeding each damage state also gradually decrease. Additionally the energy dissipation braces can greatly reduce the seismic response and the damage probability of the bridge structure.

Keywords. Reinforced Concrete Tie-beams; Double-column High-pier Rigid Frame Bridge; Energy-dissipated Brace; Near-fault Earthquake; Seismic Vulnerability

1. Introduction

The double-column high-pier rigid frame bridge has a large spanning capacity and is often used to cross mountain ravines [1]. It has a long vibration period and is a flexible system bridge. Near-fault earthquakes are characterized by short duration and high energy, and are more likely to cause damage to high-pier rigid-frame bridges. Tie-beams are an important part of the double-column piers and high-pier bridges, which has a greater impact on the seismic performance of the bridge. Traditionally, reinforced concrete tie-beams were mainly used, and there were few researches on using energy dissipation devices for double-column high-pier rigid frame bridges for damping control. Therefore, based on the seismic vulnerability analysis theory, a double-column high-pier rigid frame bridge was used as the research object to carry out the bridge vulnerability analysis, the influence of reinforced concrete tie-beams and energy-dissipated braces on the seismic performance of high-pier rigid frame bridges under near-fault earthquakes was studied.

2. Establishment of Finite Element Model of High Pier Rigid Frame Bridge

2.1. Finite element model

A five-span prestressed concrete continuous rigid frame bridge with the spans 75m+3×130m+75m is considered, and the main girder and piers are made of C50 concrete. The main girder shows a single-box single-chamber section. The box girder located at the pier top shows a height of 7.0 m. The mid-span and side-span girder end section heights are 2.5 m. The girder height along the bridge changes according to 1.8 parabola.
The cross-section of the pier adopts double-column thin-walled solid-web rectangular piers. The cross-section size of the single-limb pier is 1.2 m along the bridge, 5.6 m in the transverse direction, and the wheelbase of both legs along the bridge is 4.8 m. The finite element model of the bridge is shown in Figure 1.

![Finite element model of double-column high pier rigid frame bridge](image)

**Figure 1.** Finite element model of double-column high pier rigid frame bridge

### 2.2. Element type, Constitutive relationship and Plastic hinge

Establish a refined dynamic elasto-plastic model of a double-column high-pier rigid frame bridge, and the main girder is simulated by beam elements. The bridge pier adopts fiber element simulation that can consider nonlinear behavior. The core concrete stress-strain relationship adopts the Mander model [2] considering the Bauschinger effect. For unconstrained concrete, a concrete constitutive model without tensile zone strength is adopted. The reinforcement adopts Ramberg-Osgood simulation which can reflect the yield effect, reinforcement hardening and stiffness degradation caused by cyclic loading [3].

Plastic hinges are set at the bottom, top and closed to tie-beams of the piers, and the plastic hinges are simulated by P-M2-M3 fiber hinges. The plastic hinge length is calculated according to the empirical formula given by Pauly and Priesley [4]. Considering the consolidation of the pier and the main girder, the top node of the pier pier and the corresponding main girder node are set to be rigidly connected. The GPZ3DX one-way siding basin-type rubber bearings are set at the abutment, taking into account the frictional hysteresis of the bearing. The friction coefficient is 0.15, and the yield displacement is 0.002 m.

### 2.3. Near-fault ground motion input

The seismic fortification category of the bridge is Class B, with a fortification intensity of 7 degrees, and for Class II sites, the structural damping ratio is 0.05.

According to the site conditions of the analyzed bridge, the target spectrum is the ground motion design response spectrum of the Class II site specified in the code. Based on the PEER database, 30 near-field velocity pulse earthquake records (fault distance <25 km) are selected. The peak acceleration PGA is used as the ground motion intensity index, and the above earthquake record are adjusted to a series of earthquake record with PGA ranging from 0.1g to 1g, and the amplitude modulation increment is 0.1g. The selected typical near-fault earthquake records are shown in Figure 2.

![Selected typical near-fault earthquake records](image)

(a) PTS225 wave
3. Influence of The Number of Tied-beams on The Seismic Performance of Bridges

According to the bridge design specification and the actual situation of the built bridge, the tie-beams of the double-column piers can be set up to three at most. On the basis of the above-mentioned finite element model, keeping other structural parameters unchanged, a tie-beam was added to the pier. The cross-section size of tie-beams was designed to be 5.6m×0.8m, the longitudinal reinforcement ratio was 1.65%, and the stirrup ratio was 0.43%. The number of tie-beams is considered as 0, 1, 2 and 3 separately, and the positions of tie-beams are evenly arranged along the height of the pier. The distance between tie-beams is 40m, 20m, 13.3m, and 10m respectively, as shown in Figure 3.

The 30 selected near-fault earthquake records are input into the bridge longitudinally for IDA analysis. The IDA curves of ground motion parameters and structural performance considering different tie-beams are shown in Figure 4. The curve in the figure is the average value of the maximum structural response under the same peak acceleration under the action of 30 earthquake record.
It can be concluded from Figure 4 that whether the double-column high pier is equipped with tie-beams and the number of tie-beams have a significant impact on the dynamic characteristics of the pier. With the increase in the number of tie-beams, the curvature of the top and bottom of the double-column piers gradually decreases, and the curvature of the top of the pier decreases more rapidly. Moreover, the fewer the number of tie-beams, the more discrete the IDA curve, which means that the bridge piers are more vulnerable to damage. The curvature of the top and bottom of the pier shows no apparent difference when two or three tie-beams are set. For the support, when three tie-beams are set, the displacement response of the sliding bearings between the girder and the abutments is the smallest. The fewer the number of tie-beams, the more discrete the IDA curve, the greater the damage to the bearing supports.

Using the IDA curve results corresponding to the damage measure (DM) index, based on the vulnerability calculation theory of bridge components and the multi-dimensional system vulnerability theory, the pier top and pier bottom sections corresponding to different peak accelerations of ground motions are obtained as the DM index. The vulnerability curve of the bridge pier system is compared with the change of the vulnerability curve with the number of tie-beams in each damage state, as shown in Figure 5.
It can be seen from Figure 5 that for the pier plastic hinge of a double-column high-pier rigid frame bridge, as the number of tie-beams increases, the probability of exceeding each damage state decreases. It shows that with the increase of tied-beams, the double-column high-pier rigid frame bridge piers are less likely to be damaged. However, it can be seen from Figures 5 that when a tie beam is installed, the fragility curve under each damage state is closer to the curve when the tie beam is not installed, and there is not much difference between the two.

4. Analysis on The Damping Effect of Energy-Dissipated Braces

Energy-dissipated braces are a displacement-type energy-dissipating device, and the structure is shown in Figure 6.
In the picture: 1-end plate, 2-sleeve, 3-sliding telescopic rod, 4-high strength, 5-cover plate, 6-bottom plate, 7-boss, 8-girder, 9-pier, 10-embedded steel connection, 11-bolt, 12-stiffener, 13-synthetic anti-skid coating.

**Figure 6.** The structure of the energy-dissipated brace

In order to analyze the damping effect of the energy-dissipated brace, energy-dissipated brace was added in the middle of the four double-column piers of the basic model, and the other conditions were unchanged. At the same time, in order to fully consider the damage of the brace, the longitudinal bridge direction of the support can be freely displaced without considering the collision of the beam platform. IDA analysis is performed on the bridge subjected to 30 longitudinal earthquake records, and the vulnerability of each bridge component and the whole is calculated. In IDA analysis, the plastic hinge curvature of the pier bottom, the plastic hinge curvature of the pier top and the longitudinal displacement of the abutment support are selected as the bridge dynamic response parameters. A comparative analysis of the results when no tie-beams is added between the double-column piers and an energy-dissipated brace is added in the middle. Figure 7 shows the IDA curve corresponding to the average value of the maximum structural response under the same seismic peak acceleration under the action of earthquake record.
**Figure 7.** IDA curve of DM index changing with the connection type of double-column piers under longitudinal seismic excitation

Using the IDA curve result corresponding to the DM index, the vulnerability theory of the bridge pier system corresponding to different peak accelerations of ground motion with the cross section of the pier top and the bottom of the pier as the DM index is obtained from the vulnerability theory, and the damage conditions are compared. Compare the change of the vulnerability curve with the change of the connection form in each damage state, as shown in Figure 8.

![Figure 8](image-url)

**Figure 8.** Comparison of the influence of the double-column pier connection type on the vulnerability curve of the bridge pier under various damage states

It can be seen from Figure 8 that the addition of energy-dissipated brace between double-column bridge piers significantly reduces the vulnerability of double-column high-pier rigid frame piers in various damage states, especially for the ultimate collapse state and complete damage state. After the addition of energy-dissipated brace, the probability of exceeding the limit damage state for piers without tie-beams and energy-dissipated brace when the peak acceleration is 1g is 41% and 21%, the probability that bridge piers with energy-dissipated brace will completely collapse is reduced to zero. Moreover, judging from the trend of the vulnerability curve, the greater the seismic peak acceleration, compared with the other two cases, the greater the discrete type of the vulnerability curve, the lower the probability of damage exceeding, and the more obvious the shock absorption effect. Therefore, the use of energy-dissipated brace for double-column high-pier rigid frame bridges can greatly reduce the seismic response of the structure and reduce the damage probability of the bridge structure.
5. Conclusions

Based on the theory of fragility, the impact of tie-beams on the seismic performance of double-column high-pier rigid frame bridges under near-fault earthquakes was analyzed. It is concluded that the number of tie-beams and whether the tie-beams are energy-dissipated brace have a significant impact on the seismic performance of the bridge. The finite element simulation results show that as the number of tie-beams increase, the plastic hinge curvature of the top and bottom of the pier gradually decreases, and the probability of exceeding each damage state also gradually decreases. If the tie-beams was replaced by energy-dissipated brace, the seismic response and the damage probability of the bridge structure can be significantly reduced subjected to the earthquake.

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6. References

[1] Wang WT 1995 Rigid frame-continuous composite beam bridge[M] Beijing: China Communications Press
[2] Mander JB, Priestly MJN and Park R 1988 Theoretical Stress-Strain Model for Confined Concrete[J] Journal of Structural Engineer 14(8) pp 1806-1826
[3] Demartino A, Landofo R and Mazzdani FM 1990 The Use of Ramberg-Osgood Law for Materials Of Round-House Type [J] Materials and Structures 23 pp 59-67
[4] Priestley MJN, Sieble F and Chai YH 1992 Design Guidelines for Assessment Retrofit and Repair of Bridges for Seismic Performance [M] San Diego: Department of Applied Mechanics & Engineering Sciences University of California pp 4-34