

Response analysis of curved bridge with unseating failure control system under near-fault ground motions

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Abstract. Under the action of near-fault ground motions, curved bridges are prone to pounding, local damage of bridge components and even unseating. A multi-scale fine finite element model of a typical three-span curved bridge is established by considering the elastic-plastic behavior of piers and pounding effect of adjacent girders. The nonlinear time-history method is used to study the seismic response of the curved bridge equipped with unseating failure control system under the action of near-fault ground motion. An in-depth analysis is carried to evaluate the control effect of the proposed unseating failure control system. The research results indicate that under the near-fault ground motion, the seismic response of the curved bridge is strong. The unseating failure control system perform effectively to reduce the pounding force of the adjacent girders and the probability of deck unseating.

1. Introduction

The near-fault ground motions have strong earthquake concentration, velocity pulse characteristics, hanging wall effect and long period pulse [1], which makes the seismic response of the bridge structure under the action of the near-fault earthquake quite different from the far field. Under near-fault earthquakes, the pounding of bridge girders is very common [2-3]. Because of its flexural and torsional coupling characteristics and spatial irregularity, the seismic response of curved bridges is more complicated than that of straight girder bridges, which makes it more prone to pounding damage and unseating in the earthquake. Therefore, research of unseating failure control devices has important theoretical significance and engineering application value to improve the seismic performance of curved bridges, avoid or mitigate the serious damage of bridge structure in strong earthquakes.

Since the earthquake in San Fernando in 1971, domestic and foreign scholars have begun to study the bridge pounding and unseating problem and applied the unseating failure control devices on the bridge. Selna et al. [4] and Decrunches et al. [5] conducted a experimental research of the cable restrainers, evaluated the strength, stiffness, and deformation of the restrainers. Hao. [6], DesRoches et al. [7] and Won et al. [8] studied the seismic performance of the bridge with the restrainers installed. Their study mainly focused on the influence of the restrainers on the nonlinear seismic response of the bridge and the influence factors and laws of limit effect of the restrainers.

The research on bridge unseating failure control has obtained rich research results and applied to practical projects. However, most of the existing unseating failure control mode are a single-level control and most of them are designed for straight girder bridges. In this paper, a two-level unseating failure control system for curved bridges is proposed. The bridge unseating is controlled by the energy



dissipation restrainers and the continuous mode of the main girder respectively. Based on the multi-scale finite element model, the seismic response of the curved girder bridge under the near-fault ground motion and the effect of the unseating failure control system are studied.

2. Establishment of Unseating Failure Control System

According to both the unseating failure mechanism of concrete girder bridge and the deficiency of existing structural mode of unseating prevention systems, the new type unseating failure prevention system in this paper is created considering the following three aspects: (1) Through passive energy dissipation mechanism to reduce the structural earthquake responses, realizing seismic energy dissipation design philosophy; (2) According to different earthquake action levels to determine different performance control objectives realizing multi-failure criteria; (3) Through setting “structural fuse” to attain change of multi-level control state and avoid unreparable damage of important components due to application of restrainers realizing damage reduction philosophy.

On the basis of the above-mentioned factors, the new energy dissipation-based multi-level control system for unseating failure prevention can be established as shown in Fig. 1

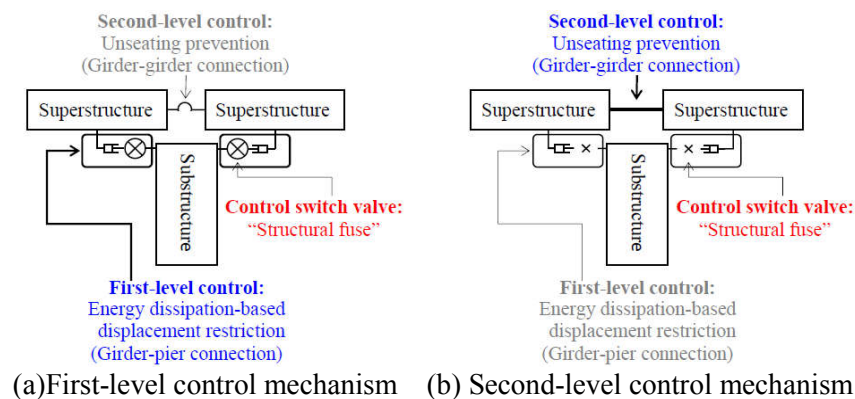


Figure 1. Unseating failure control system

3. Numerical Model

3.1. Bridge Model

Two units with three-span of $2 \times 25 + 25\text{m}$ reinforced concrete curved bridge is selected as the object of study. The first unit is two-span of $2 \times 25\text{m}$ continuous curved girders with a radius of curvature of 47.75m and the corresponding center angle is 60° . The second unit is a straight simply-support beam. The number of main girder node inside and outside of the expansion joint is N1-N4. The main girder of the bridge is a continuous box girder with C50 concrete. The bridge deck width is 9.2m and the height is 0.86m . The bridge pier use double-column circular piers. Pier height is 8m and diameter of single pier is 1.4m , spacing between two piers is 4.8m , as shown in Fig. 2. Fixed bearings are put in the bottom of pier 1 and sliding bearings are put in pier 2

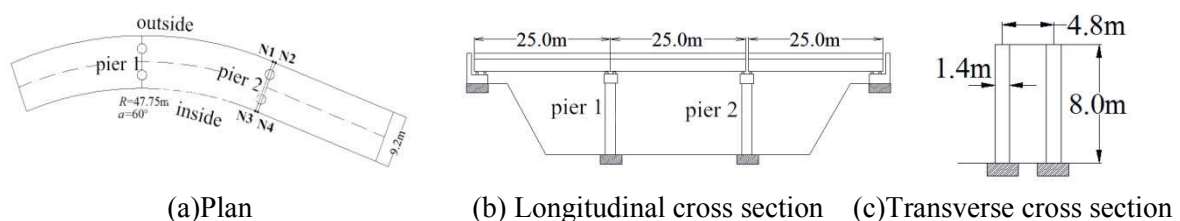


Figure 2. Structural parameter of the curved bridge.

In order to accurately simulate the seismic response of the curved bridge and reduce the computational work, a hybrid finite element model of the curved bridge is established using the general-purpose FE program ABAQUS (ABAQUS 6.12), which contains a comprehensive nonlinear analysis capacity, as shown in Fig. 3. The node DOF coordination of the interface between beam element and solid element is achieved by plane section assumption and force equilibrium condition [9]. In this paper, the influence of soil-structure interaction is ignored. All bridge piers and abutments of the FEM model are fixed on the ground.

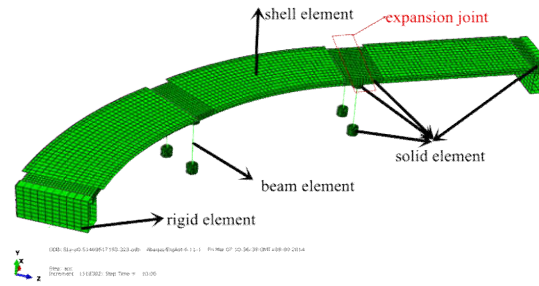


Figure 3. Finite element model of the curved bridge.

Concrete of superstructure and piers is modelled using plastic damage constitutive model proposed by McKenna [10]. Rebar is modelled using multi fold line constitutive model. Fixed bearing is modeled using elastic connection element. Sliding bearing is idealized as coulomb friction model and simulated using bilinear connection element. Three-dimensional contact - friction model [11] combined with explicit dynamic contact algorithm is used to model adjacent girder pounding of the curved bridge. The stiffness of pounding takes 0.5 times the axial stiffness of the shorter girder, and the expression is as follows:

$$K=0.5 EA/L \quad (1)$$

Where E is the elastic modulus of the main girder, A is the cross-sectional area of the main girder, L is the length of the main girder.

The damping coefficient and the damping ratio are calculated by the Eq. 2 and Eq. 3, where M_1 and M_2 are the mass of adjacent girders; e is the recovery coefficient, ξ is the damping ratio determined according to the recovery coefficient, both are in the range of 0 to 1.

$$C = 2\xi \sqrt{K \frac{M_1 M_2}{M_1 + M_2}} \quad (2)$$

$$\xi = \frac{-\ln e}{\sqrt{\pi^2 + (\ln e)^2}} \quad (3)$$

3.2. Unseating System model

The unseating failure control system proposed in this paper is modelled using connector element in ABAQUS. The restrainers between adjacent spans of first-level control is modelled using "axial" type connector element, the restrainers between span and pier of second-level control is modelled by using "axial align" type connector element. The multi-level unseating failure control system is installed at the expansion joint of the curved bridge. The specific control system is installed as shown in Fig. 4

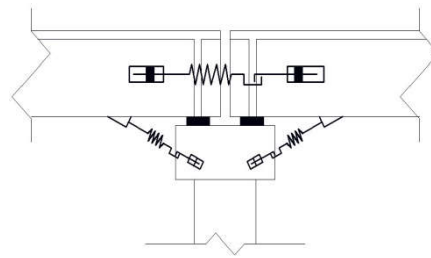


Figure 4. Control system installation diagram.

The parameter values of finite element model of unseating failure control system are given in Table. 1.

Table 1. Parameter values of the simplified model.

Parameters of unseating prevention devices	Value
Stiffness of restrained between pier and girder	$1.75 \times 10^7 \text{ N/m}$
Strength threshold of restrained between pier and girder	$1.8 \times 10^6 \text{ N}$
Stiffness of restrained between girders	$1.75 \times 10^7 \text{ N/m}$
Damping coefficient	600 N S/m
Gap of girder-pier restrained	$2 \times 10^{-2} \text{ m}$
Gap of girder-girder restrained	$3 \times 10^{-2} \text{ m}$

3.3. Ground Motion

To analyze the proposed model, a near-fault ground motion recorded by the H-E04230 station in the Imperial Valley Earthquake is selected as the seismic input of the curved bridge. The peak acceleration of the ground motion is adjusted to 0.4 g. The seismic wave is input along the direction of the main girder (curved section) of the curved bridge.

4. Results and Discussion

The responses of analytical model due to earthquake ground motion are computed with nonlinear time history analysis method. In order to evaluate the effectiveness of multi-level unseating failure control system, the nonlinear time history analysis is carried out for two analysis cases in this study: (1) Bridge A: a bridge without unseating prevention devices; (2) Bridge B: a bridge with multi-level unseating prevention devices.

4.1. Pounding Response

The time history of pounding force of the two curved bridges at the expansion joint is shown in Fig. 5. It can be seen from the figure that pounding force of adjacent girders of the curved bridge with multi-level unseating failure control system is obviously smaller than that without unseating failure control system. The maximum pounding force is reduced by unseating failure control system from 5970.7kN to 2067.7kN, reduced more than half. However, as shown in the figure, the number of pounding of Bridge B increased significantly, but pounding force values are all small. Therefore, the unseating failure control system can effectively reduce the pounding force of adjacent girders of curved bridges, seismic damage of main girders and the probability of falling beam.

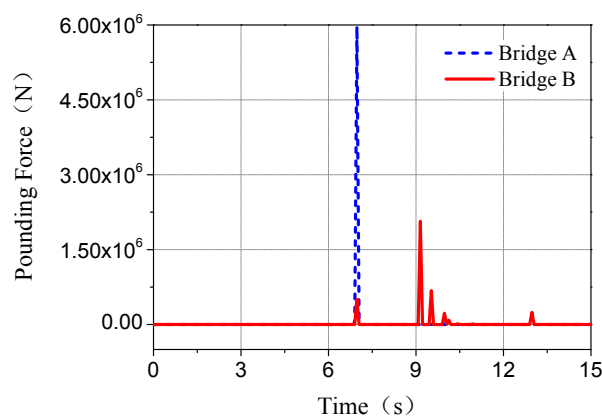


Figure 5. Comparison of pounding force of two cases.

4.2. Displacement of Main Girders

The time history of relative displacement of main girders is shown in Fig. 4.2 and Fig. 4.3. In case2, under the action of unseating failure control system, the radial relative displacement and tangential relative displacement of Bridge B is obviously smaller than that of Bridge A.

From the Fig. 6, it can be concluded that both radial and tangential relative displacement of N1 and N2 reduced through two-level unseating control failure system, especially radial relative displacement. The radial relative displacement reduced from 12.73cm to 7.12cm. Just the same as Fig. 6, it can be seen from Fig. 7 that radial relative displacement of Bridge A is considerably large because of girder pounding. However, under the action of the multi-level unseating failure control system, radial relative displacement reduced obviously, and its peak value is only 7.1cm. Comparing Fig. 6 and Fig. 7, we can find that tangential relative displacement of N3 and N4 is less than that of N1 and N2. This means that unseating of the curved bridge more likely happens from outside in the earthquake.

The effect of multi-level unseating failure control system is obvious, the relative displacement of main girders of the curved bridge is controlled well.

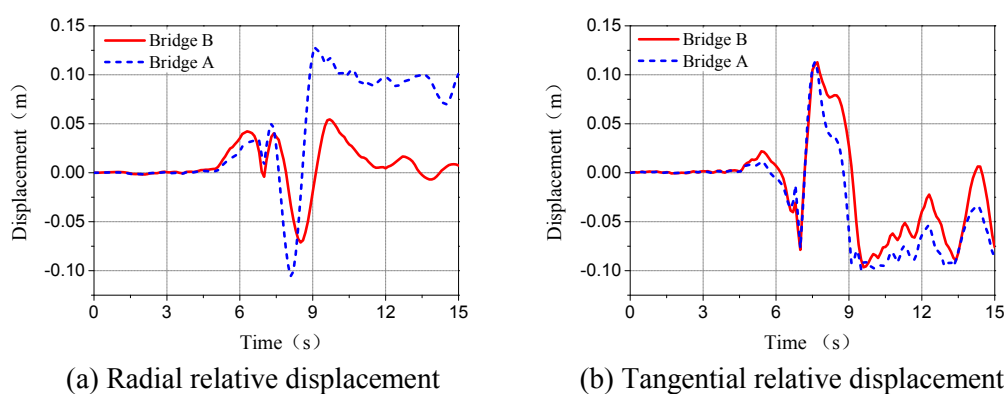


Figure 6. Relative displacement of N1 and N2.

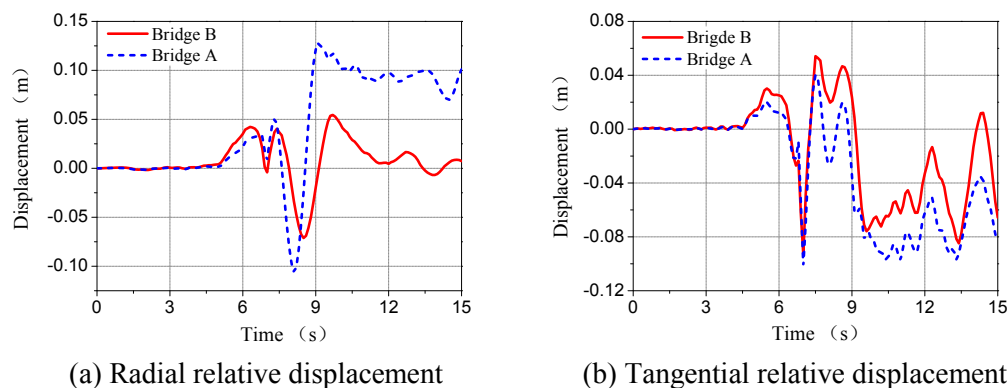


Figure 7. Relative displacement of N3 and N4.

5. Conclusion

In this paper, a new unseating failure control system is proposed to prevent unseating of the curved bridge. A multi-scale fine finite element model of a typical three-span curved bridge is established to evaluate the control effect of the proposed unseating failure control system. The seismic response of the curved bridge equipped with unseating failure control system are analyzed and compared with the curved bridge without unseating failure control system. The main conclusions are as follows:

- (1) The maximum pounding force of adjacent girders of the curved bridge is obviously reduced using unseating failure control system while the number of pounding increased.
- (2) The radial and tangential relative displacement at the expansion joint of the curved bridge is reduced especially the radial relative displacement. Unseating of the curved bridge more likely happens from outside of the curved girder.
- (3) The proposed unseating failure control system perform effectively to reduce the pounding force of adjacent girders, seismic damage of main girders and the probability of deck unseating.

Acknowledgments

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