



Seismic performance assessment of a curved bridge equipped with a new type spring restrainer



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ABSTRACT

Severe damages of curved bridge, such as pounding, unseating of superstructure and pier collapse, have been frequently observed in previous strong earthquakes. This paper demonstrates the effectiveness of a new type multi-level spring restrainer (MLSR) on reducing the seismic responses of a curved bridge. The optimal parametric values of the device are determined by response surface method (RSM). The numerical models of the curved bridge with and without MLSR are established using OpenSees. Three earthquake records are selected from PEER strong motion database matching the site condition of the bridge. Nonlinear time history analyses are performed for the bridge with and without MLSR. The force-deformation behavior of the bridge components, the relative displacements between adjacent girders, and the maximum pier curvature are evaluated. The numerical results show that the application of MLSR on the curved bridge will not only avoid the pounding and unseating of the superstructure, but also mitigate the pier damages of the bridge.

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1. Introduction

Curved concrete bridges are extensively constructed at interchanges that allow cars to move from one way to another [1]. These bridges tend to be more susceptible to strong earthquakes than straight bridges due to the inconsistent of the centers between the mass and stiffness of curved bridges. Pounding and unseating were usually seen for curved bridges during past strong earthquakes, which have attracted the attention of researchers since the failure of the I 5/14 Freeway Overpass during the 1971 San Fernando earthquake [2]. In the following two decades, the dynamic characteristics and collapse mechanism of curved bridges were comprehensively investigated. In the 2008 Wenchuan earthquake, the curved part Baihua bridge collapsed [3], mainly attributed to the insufficient support length of the transverse beam and lacking of longitudinal displacement restraints [4]. This implies that it is essential to keep the continuity between the substructure and superstructure of bridge, especially for curved bridge [5]. Another curved bridge, Huilan interchange, was also damaged in the 2008 Wenchuan earthquake. And the failure mechanism of this bridge can be summarized as below: the seismic force was concentrated on the fixed pier, which results in the flexure-shear failure of

the pier [6]. It is suggested that all the piers should be designed to uniformly undertake seismic action. Therefore, the superstructure and substructure of bridge should be appropriately connected, so that the seismic force of the superstructure would be uniformly transmitted to each pier.

Passive control has been frequently used to mitigate the seismic response of curved bridges in recent years. Isolation systems can be approximately divided into three types: isolated bearings [7–11], restrainers [12–15], and dampers [16–18]. It has been found that these passive control devices can effectively reduce the seismic responses of curved bridges. The working mechanism of these devices can either be attributed to the shift of bridge fundamental period from the dominant period of seismic excitation, or the dissipation of seismic energy by themselves. For example, cable restrainer is usually adopted to control the relative displacement between the adjacent girders of curved bridges to eliminate pounding and unseating. Meanwhile the superstructure can be isolated from seismic excitation due to the initial slack of cable restrainer. Other devices such as lead rubber bearing and viscous damper, are not frequently used in small span bridges due to high cost. Therefore, restrainers are widely adopted to connect the superstructure and substructure of bridges. The disadvantage of most restrainers is that shock may be triggered due to constant stiffness of these devices. An excellent restrainer should be characterized by providing gradually changed stiffness to absorb the

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shock and limiting the relative displacement between superstructure and substructure to a reasonable range.

The current study aims to propose a multi-level spring restrainer (MLSR), and evaluate its effectiveness on reducing the seismic responses of a curved bridge. The working mechanism and the force-deformation behavior of the restrainer are illustrated in detail. The optimal parametric values of the device are determined by response surface method (RSM). The finite element models of the bridge with and without MLSR are established using OpenSees software, and 3D nonlinear time history analyses are conducted for each ground motion. The force-deformation behavior of the bridge components, relative displacements between adjacent girders, and the maximum pier curvature of the bridge with and without MLSR are analyzed to evaluate the effectiveness of MLSR in avoiding pounding and unseating of the superstructure and mitigating the overall seismic responses of the bridge.

2. Multi-level spring restrainer (MLSR)

2.1. Working mechanism of MLSR

Fig. 1 illustrates the 3D view of MLSR. The device is mainly comprised of two systems: rail system and base system. The rail system, which includes upper plate (1), guide rail (2) and spring (3), is attached to the superstructure. Guide rail (2) is rigidly connected to the upper plate (1), and each spring (3) is applied to the end of guide rail (2). Eight guide rails (2) are symmetrically distributed in the plane of upper plate (1). The base system made up of sliding block (5), connecting rod (4), central column (7) and base plate (6), is attached to the substructure. The central column (7) is welded to the base plate (6), and the connecting rod (4) is hinged with sliding block (5) and central column (7) at each end of the rod. The rail system and the base system are linked by sliding block (5) which can only move along the guide rail (2). The working mechanism of MLSR can be explained as below: When relative displacement occurs between superstructure and substructure, sliding block (5) starts to move along guide rail (2) (Fig. 1(c)). Until the relative displacement exhausts the initial gap between the sliding block (5) and the spring (3), spring (3) starts to play its role. Then, spring (3) at each guide rail successively enter working state due to the different directions of guide rails (2). As a result, the stiffness of the device will gradually increased during this process.

MLSR is developed to provide smoothly changed stiffness for curved bridges in multi-direction, thus the shock between the superstructure and the substructure can be effectively mitigated. Meanwhile, the fundamental period of the structure can be shifted away from the dominant period of seismic excitation due to the small stiffness of the device at the initial stage. Moreover, pounding and unseating of the superstructure can be avoided because of the large stiffness of the device at the end of the stage.

2.2. Force-displacement relationship of MLSR

In order to obtain the force-displacement relationship of MLSR, the motion schematic of MLSR is illustrated in Fig. 2(a). It is assumed that an overall displacement (d) occurs in direction α ($0 \leq \alpha \leq 22.5^\circ$), then the displacement of each sliding block along corresponding rail can be calculated based on the motion of the device components. Here, the rail-spring-connecting rod in direction 2 (Fig. 2(b)) will be taken as an example. The displacement of the sliding block along the rail in direction 2 can be obtained as below:

$$u = d \cos\left(\frac{\pi}{4} - \alpha\right) + r - \sqrt{r^2 - \left(d \sin\left(\frac{\pi}{4} - \alpha\right)\right)^2} \quad (1)$$

where r is the length of the connecting rod, and d is the overall displacement of the device in direction α . If the initial gap between the sliding block and the corresponding spring is d_0 , then the spring force f_1 can be obtained:

$$f_1 = (u - d_0)k \quad (2)$$

where k is the stiffness of the spring. Here, the friction force between the sliding block and the corresponding rail is neglected for simplicity, thus the force along the axial direction of the connecting rod can be gained as below:

$$f_2 = f_1 \frac{r}{\sqrt{r^2 - \left(d \sin\left(\frac{\pi}{4} - \alpha\right)\right)^2}} \quad (3)$$

Then f_2 is projected to the direction of displacement d , and force f can be obtained:

$$f = f_2 \cos\left(\frac{\pi}{4} - \alpha - \arccos\left(\frac{\sqrt{r^2 - \left(d \sin\left(\frac{\pi}{4} - \alpha\right)\right)^2}}{r}\right)\right) \quad (4)$$

Repeating the above process for other seven directions, the force-displacement relationship of the device along direction α can be eventually obtained. Fig. 3 illustrates an example of constitutive curve of the device with the overall displacement along direction $\alpha = 0$. And the initial gap, the connecting rod length and the spring stiffness of the device are 5 cm, 20 cm and 5.0×10^5 kN/m, respectively. It can be seen from Fig. 3 that the device does not play its role when displacement within 5 cm. After the initial gap (5 cm) is exhausted, the device starts to provide gradually increased stiffness. Thus the device can not only significantly reduce the shock, but also effectively restrict the relative displacement between the superstructure and the substructure. The force-displacement relationship of the device in direction $\alpha = 0$ will be adopted in the following numerical analysis for brevity.

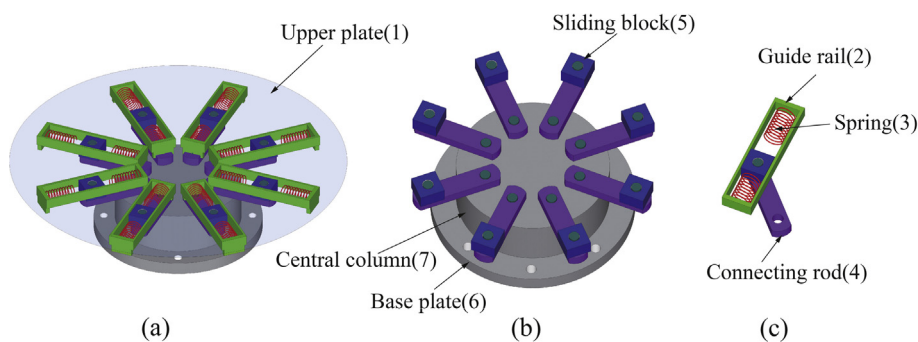


Fig. 1. Multi-level spring restrainer (MLSR): (a) general view of MLSR; (b) MLSR without rail system; (c) a single guide rail-spring-connecting rod unit;

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