

Research on Seismic Response and Damping Effect for High-Speed Railway Seismic Isolated Bridge

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Abstract: With the development of high-speed railway in recent years, lots of researchers have been paying more and more attention to the seismic isolation of high-speed railway bridge. The equivalent linear model of hysteretic characteristics of lead rubber bearings (LRB) is presented, the computational method and the varying range of dynamic parameters effecting hysteretic characteristics of LRB are established. The finite model of a high-speed railway bridge including simulating of LRB is set up by ANSYS software. The seismic responses and seismic isolation ratio of high-speed isolated bridge installed LRB are calculated, and isolation effect are compared with those fabricated the common bearings; the factors which influence seismic isolation are analyzed. The calculation results show that the bending moment and shear force of pier bottom of and displacement of grider decrease effectively for that bridge with LRB, the LRB has excellent performance on seismic isolation and energy dissipation.

Keywords: Seismic response, damping effect, high-speed railway bridge, seismic isolation, LRB

INTRODUCTION

Bridges are lifeline structures; their failure during a seismic event will result in serious consequences and will hamper relief and rehabilitation work, the considerable attention has been paid to the research of the structural seismic isolation devices for reducing the affects of earthquake disaster in recent years, the workable technology of seismic isolation is used widely in America, Japan and so on, some valuable research results have been obtained [1-7]. The main principle of seismic isolation technology is: the seismic isolation bearings can decouple superstructure from substructure, prolong the natural period of vibration of structure, increase the damping of structure, and effectively decrease seismic responses of structure. In this paper the equivalent bilinear modal and design method of dynamic parameters of LRB are established, the finite model of a high-speed railway bridge is built up, the LRB is simulated perfectly by the ANSYS software, the dynamic responses of high-speed seismic isolated bridge are calculated, the isolation effect of isolated bridge is analyzed compared with bridge installed common bearings.

HYSTERETIC ANALYSIS MODEL AND DYNAMIC PARAMETERS OF LRB

Equivalent Bilinear Model of LRB

Initial stiffness of LRB is strengthened after inserting lead-core into the ordinary laminated rubber bearing, owing

to yield strength of lead plug is lower, the pre-yield stiffness of the LRB reduces greatly which will approach to the elastic stiffness of LRB under earthquake action, the plump hysteretic curve of LRB can be obtained, it show that LRB can dissipate seismic energy effectively. Many experiments results indicate that load-deformation relationship of LRB is nonlinear, Wen *et al.* [8-10] presented the differential hysteretic resorting force model by the research on dynamic hysteretic characteristics of structure, the model approach to practical situation to some extent and later hardening properties of LRB can be considered conveniently, the restoring force can be described by the following equations:

$$F - \alpha K_1 D + (1 - \delta) Q_d z = 0 \quad (1)$$

In which, F is the hysteretic restoring force; α is the ratio of post-yield and pre-yield stiffness; K_1 is the pre-yield stiffness; D is the horizontal shear displacements of LRB; Q_d is the yielding load; z is the dimensionless form of hysteretic variation, $|z| \leq 1$, which can be calculated based on the following differential equation;

$$\dot{z} D_y - A D + \gamma |\dot{D}| z |z|^{n-1} + \beta \dot{D} |z|^n = 0 \quad (2)$$

D_y is the yielding displacement; A , γ , β are parameters which describe the hysteretic shape respectively, to LRB, $A=1$, $\gamma = \beta = 0.5$; n is feature parameter which control transition smoothness between the elastic stage and plastic stage, $n \geq 1$, to LRB, $n = 2$.

The two-step solution algorithm is employed to solve the hysteretic model of LRB, that is, the unconditionally stable

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Newmark's constant-average-acceleration method is employed to solve the motion equation, and the unconditionally stable semi-implicit Runge-Kutta method is used to solve the differential equations governing the behavior of the nonlinear isolation elements.

As can be seen that Wen model is complicated to design of LRB, the hysteretic curve can be simplified into the bilinear curve by assuming effective stiffness and effective damping ratio for the sake of convenient in engineering application, the simplified method is made use of in ETABS, SAP and AASHTO [11], JPWRI [12], NZMWD [13], etc. The equivalent bilinear modal of LRB is shown in Fig. (1).

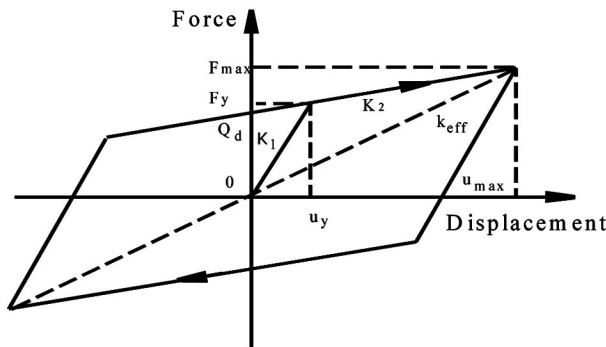


Fig. (1). Equivalent bilinear modal of LRB.

DYNAMIC PARAMETERS OF LRB

The computing formulas of the equivalent stiffness and damping of LRB which are presented in this-paper according to AASHTO [11].

$$K_{eff} = \frac{1 + \alpha(\mu - 1)}{\mu} K_1 \tag{3}$$

$$\xi_{eff} - \xi_0 = \frac{2(1 - \alpha)(\mu - 1)}{\pi\mu[1 + \alpha(\mu - 1)]} \tag{4}$$

For the ideal bilinear model

$$K_{eff} = K_2 + \frac{Q_d}{d} \tag{5}$$

$$\xi_{eff} = \frac{2Q_d(d - d_y)}{\pi K_{eff} d^2} \tag{6}$$

In which, K_{eff} is the equivalent stiffness; ξ_{eff} is the equivalent damping; K_1 is the pre-yield stiffness K_2 is the post-yield stiffness; Q_d is the characteristic strength of LRB; d is the design total deck displacement relative to ground; d_y is yield displacement of LRB; $\alpha = \frac{K_2}{K_1}$ is the hardening ratio; ξ_0 is the damping ratio of structure.

The computational formulas of post-yielding stiffness and characteristic strength of LRB are presented in reference [11].

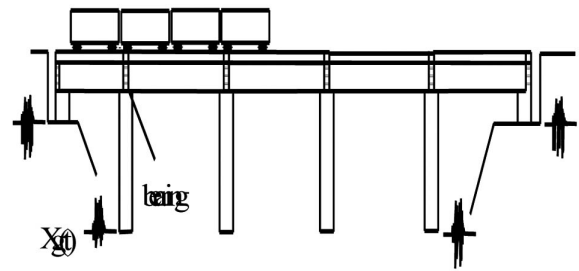


Fig. (2). Model of five-span simply supported bridge.

EARTHQUAKE RESPONSES ANALYSIS CASE OF SEISMIC ISOLATED BRIDGE

Basic Parameters of Five-Span Simply Supported Bridge

A five-span simply supported box bridge under high-speed trains is taken as the calculation model to analyze the damping effect of seismic isolated bridge in this paper, the related parameters are listed below: 32 m span concrete prestressed concrete box girder, 2.3m×6.0m round-shaped solid piers which are cast in situation and concrete strength grade is C35, the designed horizontal earthquake acceleration $a=0.2g$, the rare horizontal earthquake acceleration $a=0.4g$. The finite element model of five-span simply supported bridge is shown in Fig. (2).

SIMULATING OF LRB

The ANSYS software is employed to establish the space analysis model of the five-span simply supported box bridge under high-speed trains in this paper, the Beam 188 element is utilized to simulate box beam and pier, the bottom of piers is proposed consolidated not considering Soil-Pile Interaction. Nowadays the pot rubber bearings have been widely used in the high-speed railway bridge, the Combin 14 unit is employed to simulate horizontal and vertical stiffness of the pot rubber bearings; the mechanical model of isolation bearing can be predigested to the model which are made up of the nonlinear spring and damper in two horizontal direction and the linear spring in the vertical direction, the Combin 14 element is employed to simulate vertical stiffness; the Combin 40 element is employed to simulate horizontal stiffness in two horizontal directions, the influence of bilinear hardening model and damper in the Combin 40 element can be considered effectively.

THE DESIGN OF LRB

The dimension and corresponding calculation parameters of LRB are shown in Table 1 according to the theory and methods mentioned above.

SELECTION OF SEISMIC GROUND MOTIONS AND TRAIN LOAD

Code for seismic design of railway engineering [14] provides that: the horizontal earthquake action along the longitudinal and the transverse direction should be calculated respectively for the aseismic checking computation of bridge, the most disadvantaged force combinations are $Ex+0.65Ex$

Table 1. Dimension and Calculation Parameters of LRB

Number of LRB	Number of Lead Plug	Diameter of LRB(mm)	Height of LRB(mm)	Diameter of Lead Plug(mm)	Pre-yield stiffness(kN/mm)	Post-yield Stiffness (kN/mm)	Yield Load(kN)
2	4	1100	200	100	36.90	5.67	512

and $E_y+0.65E_y$. In this paper, El Centro wave, Taft wave and Parkfield wave are used to calculate the seismic responses of bridge, length of be confined to, the paper list only the computation results of seismic ground motions of El Centro earthquake wave. ICE high-speed train of Germany is employed as the vehicle live load, the train marshalling is: $2 \times (\text{train} + \text{train} + \text{trailer} + \text{train} + \text{train} + \text{trailer} + \text{train} + \text{train})$. The acceleration time history curve of earthquake wave are given in Figs. (3-5).

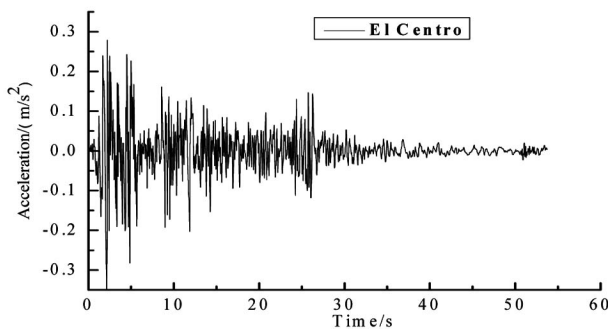


Fig. (3). Acceleration time history curve of El Centro earthquake wave.

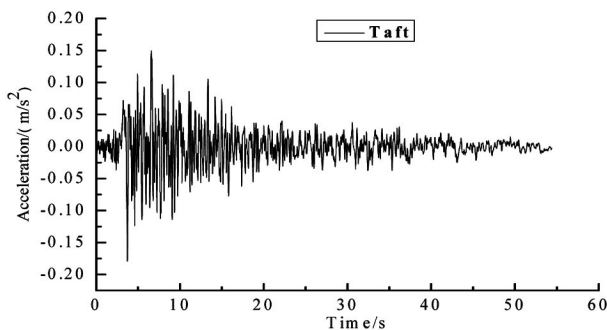


Fig. (4). Acceleration time history curve of Taft earthquake wave.

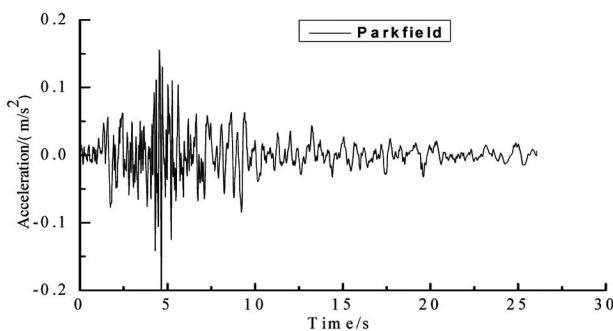


Fig. (5). Acceleration time history curve of Parkfield earthquake wave.

CALCULATING AND ANALYZING OF DYNAMIC RESPONSES OF HIGH-SPEED RAILWAY BRIDGE FABRICATED LRB

Working Conditions

In this paper, three sorts of working conditions and their combinations are considered for analyzing the seismic responses and the seismic isolation effect of the seismic isolated bridge.

- (1) The bridge fabricated common bearings or LRB are considered respectively, the dimension and corresponding calculation parameters of LRB are shown in Table 1;
- (2) The trains pass over bridge at the speed of 160 km/h, 200 km/h, 250 km/h, 300 km/h, 350 km/h;
- (3) Three sorts of typical strong motion recordings in site are input, lateral and longitudinal design earthquake and severe earthquake are considered respectively, adapting force combinations of $E_x+0.65E_x$ and $E_y+0.65E_y$;

Fundamental period of bridge before seismic isolation is 0.592s, after seismic isolation is 0.888s. The dynamic time-history responses are calculated by inputting different strong motion recordings and earthquake strength. The seismic responses time-history curve of pre-and post-seismic isolated bridge under transverse design earthquake with 160 km/h train speed and 14m pier height are seen in Figs. (6-8); the seismic responses time-history curve of pre-and post-seismic isolated of bridge under transverse severe earthquake with 350 km/h train speed and 14m pier height are seen in Figs. (9-11); the seismic responses of pre- and post- seismic isolated bridge and the seismic isolation ratio with 350 km/h train speed and 14m pier height under lateral severe earthquake are seen in Table 2.

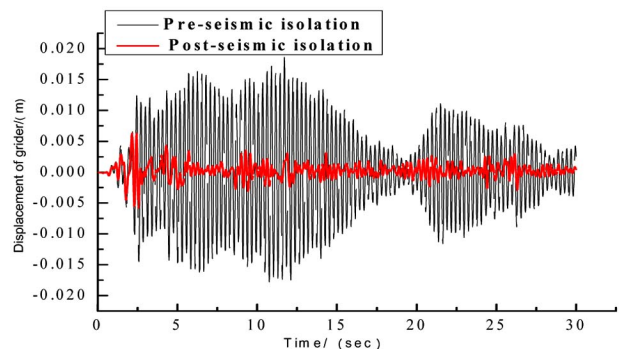


Fig. (6). Time-history curve of pre-and post-seismic isolation displacement of girder under transverse design earthquake with 160 km/h train speed an 14m pier height.

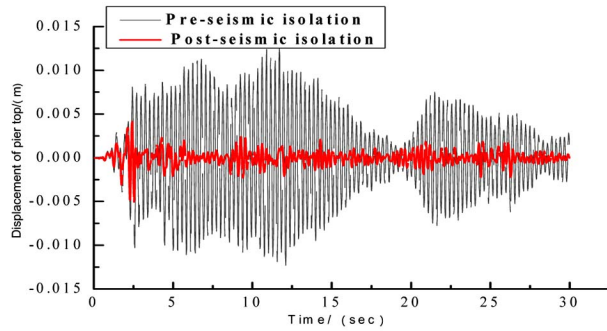


Fig. (7). Time-history curve of pre-and post-seismic isolation displacement of pier top under transverse design earthquake with 160 km/h train speed and 14m pier height.

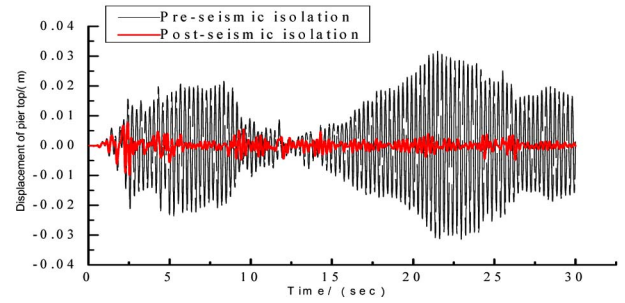


Fig. (10). Time-history curve of pre-and post-seismic isolation displacement of pier top under transverse severe earthquake with 350 km/h train speed and 14m pier height.

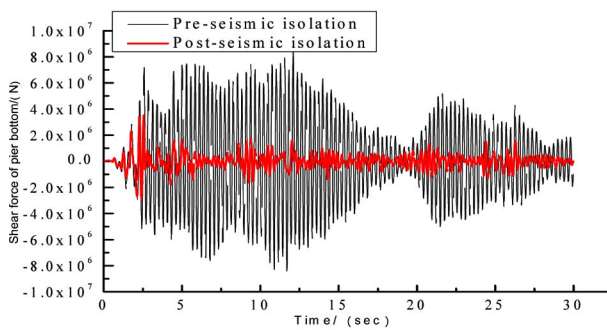


Fig. (8). Time-history curve of pre-and post-seismic isolation shear force of pier bottom under transverse design earthquake with 160 km/h train speed and 14m pier height.

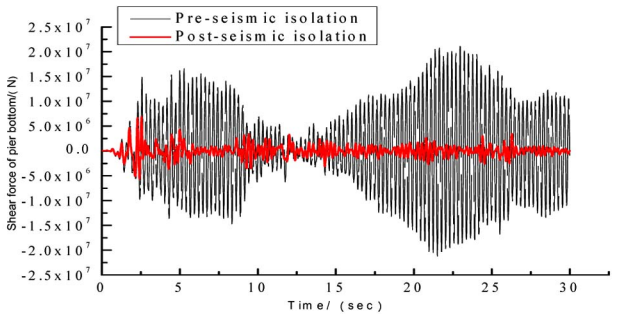


Fig. (11). Time-history curve of pre-and post-seismic isolation shear force of pier bottom under transverse severe earthquake with 350 km/h train speed and 14m pier height.

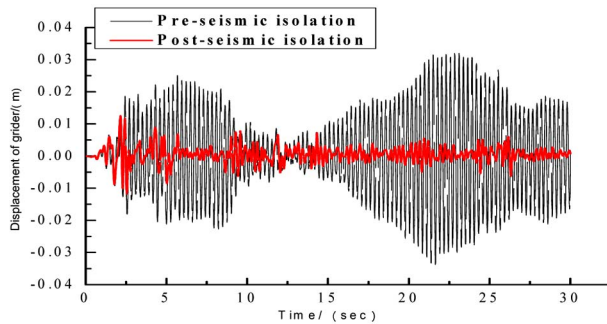


Fig. (9). Time-history curve of pre-and post-seismic isolation displacement of girder under transverse severe earthquake with 350 km/h train speed and 14m pier height.

Table 2. Responses of Pre- and Post- Seismic Isolation and Seismic Isolation Ratio with 350 km/h Train Speed and 14m Pier Height Under Lateral Severe Earthquake

Responses of Bridge	Transversal Displacement of the Grider(m)	Transversal Displacement of Pier-top(m)	Shearing Force of Pier-Bottom(N)
Responses of pre- seismic isolation	0.0269	0.0250	1.680e7
Responses of post- seismic isolation	0.0125	0.00828	7.035e6
Seismic isolation ratio (%)	53.5	66.9	58.1

*Seismic isolation ratio $\lambda_e = \frac{e_0 - e}{e_0}$, λ_e is seismic isolation ratio, e_0 is maximum response of structure without dampers; e is maximum response of structure with dampers.

Calculation results show that: (1) the seismic responses of the bridge will increase nonlinearly with the rise of the train speed; (2) the seismic isolation effect is comparatively satisfactory when design period is about 1.5 times of the natural vibration period, if design period is larger, the design displacement will increase, the seismic isolation effect becomes bad; (3) the seismic responses can be reduced effectively and seismic response curves are relatively stable after seismic isolation, the seismic isolation ratios are in the range of about from 50.0% to 70.0%.

CONCLUSIONS

In this paper, the equivalent bilinear model of hysteretic characteristics of LRB is established, the calculation method and reasonable varying range of dynamic parameter of the seismic isolation device are presented, and the calculation result shows that:

- (1) The seismic responses of the bridge will increase with the rise of earthquake intensity;

- (2) Because of the strong excitation action of the earthquake, the influence of the vehicle live loading is slight, the seismic responses of the bridge will increase nonlinearly with the rise of the train speed;
- (3) Compared to the common bearing, the LRB can reduce not only the displacement of pier top under earthquake, but also the bending moment and the shear force of the bridge are reduced greatly at the same time; the seismic responses reduce effectively and the seismic response time-history curves are relatively stable after seismic isolation, the seismic isolation effect is satisfactory;
- (4) The selection of dynamic parameters of LRB is the key to reduce the seismic responses of structure, moreover; the parameter optimization of seismic isolation device of bridge should be emphasized in further research.

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