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Numerical Investigation on Seismic Responses of High-speed Railway Isolated Bridge with Lead Rubber Bearings

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Abstract: This paper presents the seismic isolation design method developed for nonlinear dynamic analysis of three-dimensional-isolated-railway bridge with lead rubber bearings. The equivalent bilinear modal and calculation method of dynamic parameters of lead rubber bearings are established, the seismic responses of pre-and post-seismic isolation of bridge are calculated, the effect of different vehicle speed and earthquake strength on the performance of seismic isolated bridges are analyzed. The results indicate that the seismic response of bridge decrease significantly after being isolated, the seismic isolation ratio is approximately between 60-70%.

Keywords: Seismic responses, High-speed railway, Isolated bridge, Seismic isolation, Lead rubber bearings

1 Introduction

Since the lead rubber bearings (LRB) were used in New Zealand in 1978, the seismic isolation technology have been widely employed in engineering practice in America, Japan and so on, many scholars have been made extensive and profound studies on the seismic isolation technology recently, some valuable researches have been obtained [1-4]. The existing researches focused on the highway bridge, with the rapid development of the high-speed railway, lots of researchers have been paying more and more attention to the seismic isolation of the high-speed railway bridge, it is becoming the key to seismic isolation design of railway bridge how to decrease effectively bending moment, and the displacement of girders do not increase distinctly in accordance with the transverse vibration requirements of railway bridge codes.

In this paper, the equivalent bilinear modal and the calculation method of dynamic parameters of the LRB are presented, the finite element model of the bridge is established, the dynamic responses of pre- and post-seismic isolation of bridge are calculated, and seismic isolation effect of LRB is analyzed. The calculation results can provide reference for seismic design of railway bridge.

2 Equivalent Bilinear Modal of LRB

Test and theory analyses indicate that the load-deformation relationship of LRB is nonlinear, based on the uniaxial differential hysteretic resorting force model of Wen[5] and the biaxial differential hysteretic resorting force model of Park [6] et al, Nagarajaiah [7] proposed the uniaxial and biaxial coupled elasto-viscoplastic differential hysteretic resorting force model, which can simulate perfectly the resorting force characteristics of LRB, the resorting force of LRB can be the combination of linear spring and viscous dampers in the Nagarajaiah modal.

The restoring force of LRB can be described by follow equation

$$q = \alpha \frac{F_y}{u_y} x + (1-\alpha) F_y z \qquad (2.1)$$

In which, q is hysteretic restoring force; α is post-yielding to pre-yielding stiffness ratio; F_y is yielding force; u_y is the yield displacement; z is the hysteretic dimensionless quantities; $|z|\le 1$, which can be calculated based on the differential equation.

$$u_y \dot{z} = A\dot{u} - \gamma|\dot{u}|\,z\,|z|^{n-1} - \beta\dot{u}|z|^n \qquad (2.2)$$

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 elastic stage and plastic stage, $n \ge 1$, to LRB, n =2

The two-step solution algorithm is used to solve the differential equation above, the first step is the solution of equations of motion using the unconditionally stable Newmark's constant-average-acceleration method, and the second step is the solution of differential equations governing the behavior of the nonlinear isolation elements using the unconditionally stable semi-implicit Runge-Kutta method.

3 Dynamic Parameters Design of LRB

The equivalent bilinear analysis does not directly applied for the structures design in traditional earthquake-resistent design, because the seismic effect coefficient is used to reduce the earthquake force in linear elastic design, the details of seismic measures are carried out to ensure the ductility index. The design earthquake strength is directly applied for the seismic isolation design without considering the strength reduction factoring in design of isolated bridge; therefore, the equivalent bilinear analysis is necessary. The Wen model, the Park model and the Nagarajaiah model are complicated that it is not suitable for the design from the theory analysis above; the hysteretic curve can be simplified to bilinear curve by the proposed effective stiffness and damping ratio, the equivalent bilinear modal of LRB is established, which are used in ETABS, SAP program and the codes of AASHTO[8], JPWRI[9] and NZMWD[10]. The equivalent bilinear modal of LRB is seen in Fig 3. 1.

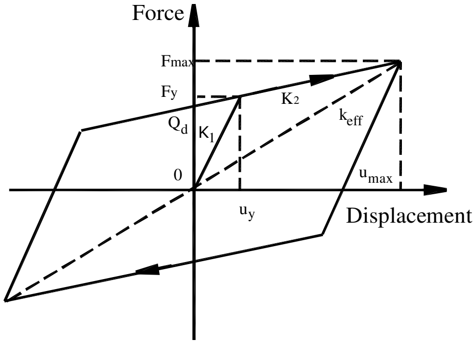


Fig 3.1 Equivalent bilinear modal of LRB

The computing formulas of the equivalent stiffness and damping ratio of LRB which are presented in this paper according to AASHTO [8].

$$K_{eff} = \frac{1+\alpha(\mu-1)}{\mu} K_1 \qquad (3.1)$$

$$\xi_{eff} - \xi_0 = \frac{2(1-\alpha)(\mu-1)}{\pi\mu[1+\alpha(\mu-1)]} \qquad (3.2)$$

For the ideal double linear model

$$K_{eff} = K_2 + \frac{Q_d}{d} \qquad (3.3)$$

$$\xi_{eff} = \frac{2Q_d(d-d_y)}{\pi K_{eff} d^2} \qquad (3.4)$$

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

According to AASHTO [9], the detailed procedure of dynamic parameters of LRB is given below.

At first, the proposed seismic isolation period and effective damping ratio is determined, the earthquake force of the structure can be calculated.

$$F = C_s W \qquad (3.5)$$

$$C_s = \frac{K_{eff} \times d}{W} \qquad (3.6)$$

$$T_{eff} = 2\pi\sqrt{\frac{W}{gK_{eff}}} \qquad (3.7)$$

The total displacement of LRB is

$$d = \left(\frac{T_{eff}}{2\pi}\right)^2 gC_s \tag{3.8}$$

The sum of the effective linear stiffness of all bearings and substructures supporting the super structures segment.

$$K_{eff} = \left(\frac{2\pi}{T_{eff}}\right)^2 W \tag{3.9}$$

$$K_1 = 6.5K_2 \tag{3.10}$$

According to the formulas of the equivalent stiffness and damping ratio of LRB, the dynamic parameters of LRB can be calculated.

C_s is the elastic seismic response coefficient; W is the total vertical load for design of the isolation system(dead load + seismic live load); K_{eff} is the sum of the effective linear stiffness of all bearings and substructures supporting the super structures segment in the design of LRB; T_{eff} is the period of seismically isolated structure, in seconds, in the direction under consideration; g is the acceleration due to gravity; G is shear modulus of elastomer, G =1.0MPa; [τ] is the yield shear stress of lead core plug, [τ]=8.5 MPa.

After the pre-yield stiffness, the pre-yield stiffness, the characteristic strength of LRB is calculated, the dimension, diameter of lead plug and height of LRB can be obtained according to the support forces.

4 Modeling of LRB and Vehicle-bridge System

The ANSYS software and ANSYS-APDL program are employed to establish the space analysis model of one multi-span simply supported box bridge under high-speed trains in this paper, the Beam 188 to be utilized to simulate box beam and pier element, the pier bottom is proposed consolidated. Finite element model of bridge systems is shown in Fig 4.1.

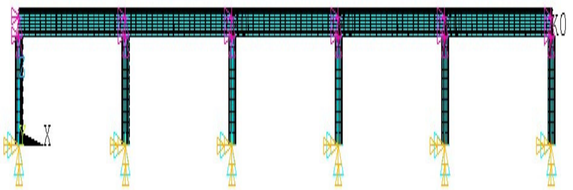


Fig 4.1：Finite element model of bridge systems

ICE series high speed vehicle is of Germany is employed as vehicle live load; the vehicle is modeling by spring-mass system, the rail random irregularities turbulence is inputted. The parameters of ICE series high speed vehicle can be seen in reference [11]. The track vertical profile irregularity is seen in Fig 4.2.

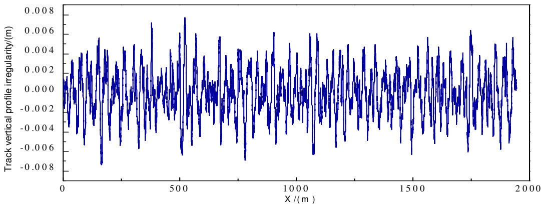


Fig 4.2 Track vertical profile irregularity of German railway spectra of low irregularity

Nowdays the pot rubber bearing has been widely used in high-speed railway bridge especially concrete box-beam bridge, the mechanical model of pot rubber bearing can be simplified a model which is made up of nonlinear spring in two horizontal and vertical direction, the Combin14 element is employed to simulate horizontal and vertical stiffness in ANSYS. The mechanical model of isolation bearing can be predigested to a model which is made up of the nonlinear spring and damper in two horizontal direction and the linear spring in the vertical direction, the Combin14 element is employed to simulate vertical stiffness; the Combin40 element is employed to simulate horizontal stiffness in two horizontal direction, the influence of bilinear hardening model and damper can be considered in Combin 40 element perfectly.

5 Case Study

Take a five-span simply supported box bridge system as an example; the responses of the third span can presented the responses of the whole bridge system, the related parameters are listed below: 32-m span concrete box girder, 2.3×6.0 reinforced concrete piers, concrete strength grade C35, the designed earthquake acceleration a=0.2g, the severe earthquake acceleration a=0.4g.

ICE series high speed trains of Germany is employed as train live load, train marshalling: vehicle marshalling: 2× (locomotive + locomotive + truck + locomotive + locomotive + truck + locomotive + locomotive).

In this paper, the seismic responses of bridge along the longitudinal and transverse direction are calculated respectively, the most disadvantaged earthquake force combinations are Ex + 0.65Ex and Ey + 0.65Ey. In this paper, El Centro, Taft and Parkfield earthquake wave are used to calculate the responses of bridge system, length of be confined to, the paper list only the computation results of seismic ground motions of El Centro earthquake.

According the theory analysis above, the dimension and design parameters of LRB with 12m pier height are shown in Table 5.1.

Table 5.1: Dimension and calculation parameters of LRB

Number of lead plug	Diameter of lead core (mm)	Height of LRB(mm)	Diameter of lead plug(mm)
4	100	230	180
Diameter of LRB(mm)	Pre-yield stiffness(kN/mm)	Post-yield stiffness (kN/mm)	Yield load(kN)
1100	252.7	38.9	790.0

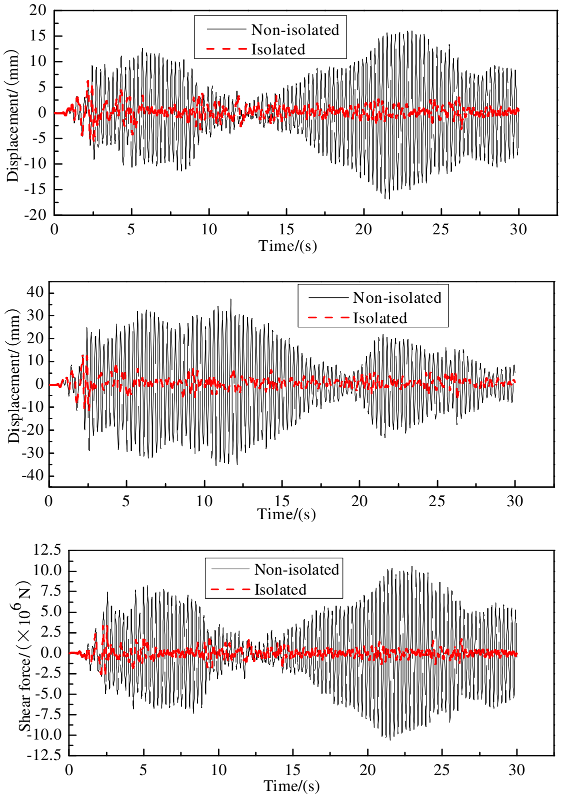


Fig 5.1: Time-history curve of displacement of grider, displacement of pier top and shear force of pier bottom with 350km/h train speed and 12m pier height under transverse design earthquake

5.1 Effect of vehicle speed on Performance of Seismic Isolated Bridges

To investigate the effect of vehicle speed on the performance of seismic isolated bridges, it is specified that the train marshalling pass over bridge system at the speed of 160km/h, 200 km/h, 250 km/h, 300 km/h, 350 km/h, the ANSYS-APDL grogram is implemented to make the whole train marshalling always travel on the bridge during the earthquake action time. The time-history curve of seismic responses of pre-and post-seismic isolation with 350km/h train speed and 12m pier height under transverse design earthquake are shown in Fig 5.1; the seismic responses of pre-and post-seismic isolation with different train speeds and 12m pier height under transverse design earthquake are shown in Fig 5.2.

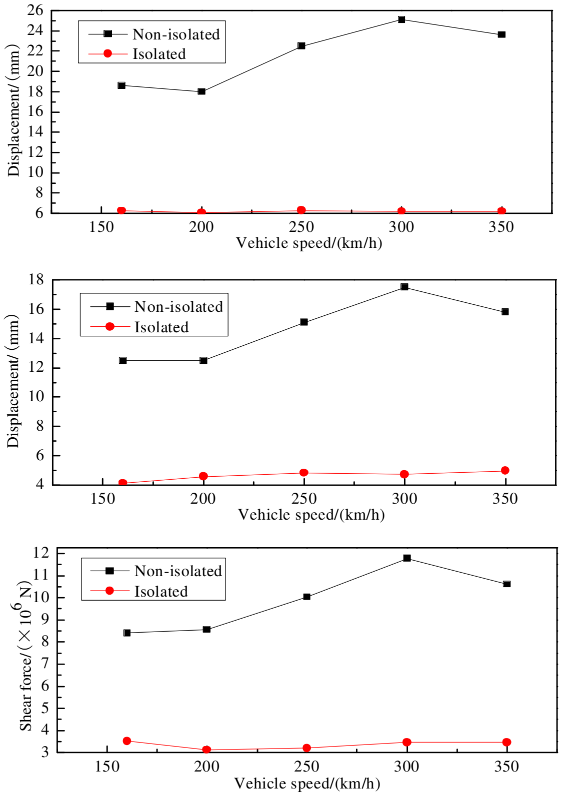


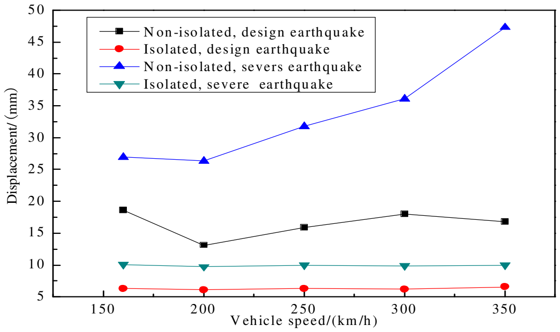
Fig 5.2: Displacement of girder, displacement of pier top and shear force of pier bottom with 350km/h train speed and 12m pier height under transverse design earthquake

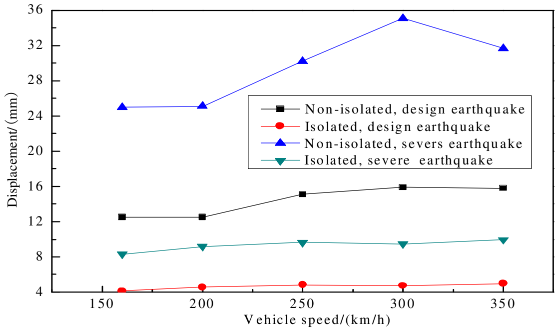
The calculation results show that: (1) When the design is 1.5 times of the natural period, the seismic responses of seismic isolated bridge increase slightly with increasing of vehicle speed, the seismic isolation ratio change smoothly which is approximately between 60-70%; (2) The deformation of bearings decrease dramatically, it vary little with the increase of the vehicle speed; (3) The LRB has excellent performance of seismic isolation and energy dissipation, bending moment and shear force of pier bottom of bridge can be effectively decrease, not increase displacement of girder and bearings when the dynamic parameter of LRB are reasonably determined.

5.2 Effect of earthquake strength on Performance of Seismic Isolated Bridges

To investigate the effect of the earthquake strength on the performance of seismic isolated bridges, the seismic responses are calculated under the design (a=0.2g) and severe (a=0.4g) earthquake, the force combinations of Ex + 0.65Ex and Ey + 0.65Ey are used as earthquake ground motion excitation, Ex presents earthquake force in the longitudinal direction, Ey presents earthquake force in the lateral direction, 0.65Ex and 0.65Ey present the earthquake force in the vertical direction. The displacement of girder, displacement of pier top, shear force of pier bottom and seismic isolation ratio of pre- and post- seismic isolation with 12m pier height and different train speeds under lateral design/severe earthquake is shown in Fig 5.3.

The calculation results show that: (1) The seismic responses rapidly increase with the increasing of the earthquake strength; (2) The seismic responses of the seismic isolated bridge distinctly reduce, the seismic isolation ratio increase with the increasing of the vehicle speed, the seismic isolation effect is better for the structure under the severe earthquake action.





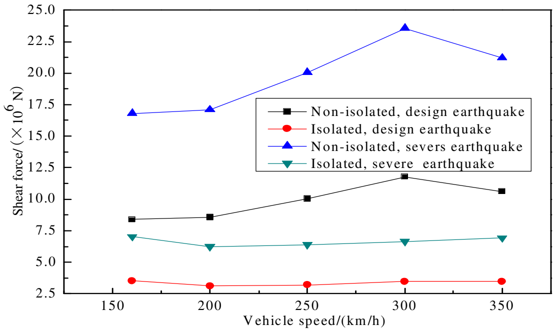


Fig 5.3: Displacement of grider, displacement of pier top and shear force of pier bottom with 12m pier height and different train speeds under lateral severe earthquake

6 Summary

In this paper, the equivalent bilinear modal and calculation method of the dynamic parameters of LRB are presented; the seismic isolation effect of high-speed railway seismic isolated bridge is analyzed. Calculation results show that.

(1) The seismic responses of bridge increase in non-monotonously linear manner with the increase of vehicle speed, the seismic responses remarkably reduce and the time-history curves are stable after the bridge is isolated, the lateral displacement of the girder and pier distinctly reduce, it is significant for the railway bridge.

(2) The seismic responses rapidly increase with the increasing of the earthquake strength, the seismic isolation effect of the seismic isolated bridge is better under severe earthquake action.

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