RESEARCH ON SEISMIC ISOLATION DESIGN FOR HIGH-SPEED RAILWAY SIMPLY-SUPPORTED GRIDER BRIDGE

ZOU Shuang(1) , WENLIUHAN. Heisha(1), LIU. Yanhui(1), ZOU Fulin(1)

(1)Research Assistant, State Key Laboratory for Seismic Reduction/Control & Structure Safety(Cultivation base),Guangzhou University, Guangzhou, China, Zoushuang_2015@163.com

Abstract
In this paper a new seismic isolation system was presented for a high-speed railway simply-supported girder bridge. And on the basis of the optimization theory, the optimal design model of the seismic isolation high-speed railway simply-supported girder bridge was established. Considering the longitudinal displacement of the beam and the pier shear of the pier as the constraint conditions, and the maximum of the bending moments at the bottom of piers as the objective function, the optimization method of the SQP was used to realize the performance parameters optimal design of the new seismic isolation system under seven earthquake waves. The results show that the new seismic isolation system have the effect of reduction control the longitudinal displacement of the beam, the pier shear force was reduced drastically. Through calculation analysis, the influence rules of performance parameters of the new seismic isolation system on bridge seismic responses are given.
Keywords: Seismic isolation system, high-speed railway, simply-supported grider bridge, optimal design, performance parameter

1. introduction

High-speed railway has the advantages of large transport capacity, high speed, high security and small affected by climate, so it has developed rapidly around the world. On 1 October 1964, the world's first high-speed railway Tokaido Shinkansen trains in Japan was opened to traffic, whose maximum operating speed was 210km / h, a few years later increased to 270km / h gradually. June 1991 and June 1992, Stuttgart, Mannheim, Germany a line and Hanno - Würzburg line was built, and the highest running speed of the train was 270km/h. In recent years, our high-speed railway development rapidly. Beijing-Tianjin Intercity Railway, Wuhan-Zhengzhou line, Beijing-Shanghai high-speed railway has been opened, speed up to 300km / h [1].

With the rapid development of high-speed railway, seismic isolation issue of high-speed railway under earthquake attract more and more attention of the scholars. In recent years, many buildings and the bridge structures have adopted seismic isolation technology. Seismic isolation technology mainly through using seismic isolation devices to separate the structure or components from ground motion or carriage movement may cause damage as much as possible. Thus it greatly reduce the seismic forces and energy transmitted to the upper structure. The bridge structure was connected of the beam and the pier by a bearing . Isolation bearing was installated at the junction of the beam and the pier, such as laminated rubber bearing, Lead Rubber support Block et al [2]. By extending the construction period, the increase of structural damping, can effectively reduce the seismic response of structures. However, due to the several isolation bearing vertical bearing capacity is not enough high, and therefore only be applied in small and medium-span continuous rail and road bridges [3].

Based on the above problems, in order to allow seismic isolation technology to give the high-speed railway simply-supported girder bridge better service , this paper presents a new seismic isolation system. The new seismic isolation system was installed between the bottom of the beam and the top of the pier. When an earthquake occurs, in elastic working stage of the pier, the new seismic isolation system dose not work, so give full play to the pier seismic effect to limiting the longitudinal displacement of the beam. In elastic-plastic working stage of the pier, on the basis of in guaranteeing that piers are not yield and the longitudinal displacement of the beam meet the design requirements, the new seismic isolation system play hysteretic energy characteristics to minimize simply-supported bridge seismic force. On the basis of the optimization theory, the optimal design model of a high-speed railway simply-supported girder bridge with the new seismic isolation system was established, considering the longitudinal displacement of the beam and the pier shear as the constraint conditions, the maximum of the bending moments at the bottom of the pier as the objective function.

The optimization method of the SQP was used to realize the performance parameters optimal design of the new seismic isolation system under seven earthquake waves. For high-speed railway simply-supported girder bridge seismic isolation design provides an effective method and reasonable basis.

2. Seismic isolation design for high-speed railway simply-supported girder bridge

2.1 Summary of the new seismic isolation system

Seismic isolation design of large-span bridges mainly has two ways. First is how to reduce the seismic force of a fixed pier effectively, and the second is seismic isolation device must have a high vertical bearing capacity[2]. Further, the high-speed railway bridge has higher requirements on the longitudinal displacement of the beam. Therefore, in addition to effectively control the seismic force and vertical bearing capacity, strictly control of the longitudinal displacement of the beam is also an important indicator for the high-speed railway bridge seismic isolation design. Based on this, in this paper, a new seismic isolation system is proposed. As shown in figure 1, the new seismic isolation system is composed of two double spherical isolation bearing and a lead rubber bearing(Hereinafter referred to as LRB). By means of such structure, the new seismic isolation system can not only give full play to the advantages of the vertical bearing of the double curved spherical bearing, also can exert the characteristics of the hysteretic energy dissipation of the LRB.

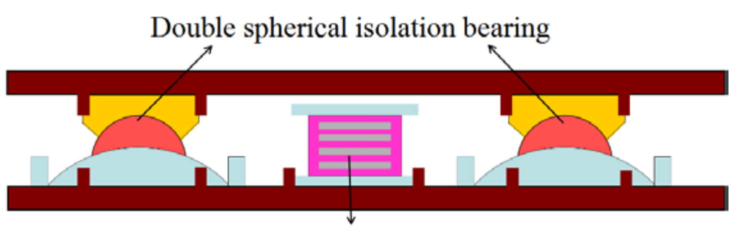

Fig. 1– New seismic Isolation system

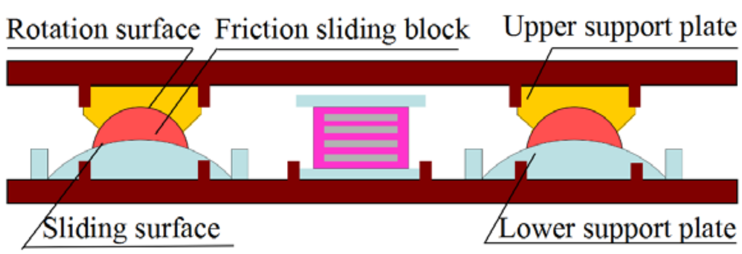

Fig. 2 – Structure of double spherical isolation bearing

2.2 Double spherical isolation bearing

Double spherical isolation bearing is a kind of dry friction-sliding isolation device. As shown in figure 2, the double spherical isolation bearing consists of an upper support plate, a lower support plate, and an intermediate joint type friction sliding block. The mechanism has two contact surfaces. The lower sliding surface is used to complete the energy dissipation, and the upper rotation surface is used to adjust the position of the supporting seat.

The damping principle of double spherical isolation bearing is divided into the following two process. When the horizontal force generated by the earthquake action is less than the friction force of the bearing, the double spherical isolation bearing is not sliding and the lateral stiffness is only provided. When the horizontal force generated by earthquake action is larger than the friction force of the bearing, the sliding surface is free to slide and the earthquake energy is consumed by the friction damping force. The structure period is prolonged to achieve the purpose of damping seismic. Different damping effect can be achieved by adjusting the rotation radius of the support.

In this study, in order to simplify the calculation, the stress-strain curve of the ideal elastic plastic material(as shown in figure 3) is used to approximate the dynamic hysteretic curve of the double spherical isolation bearing. Assume that the elastic stiffness of bearing is infinite. x is displacement. $F(x)$ is friction force. F_y is critical friction. μ is coefficient of sliding friction, m is vertical load.

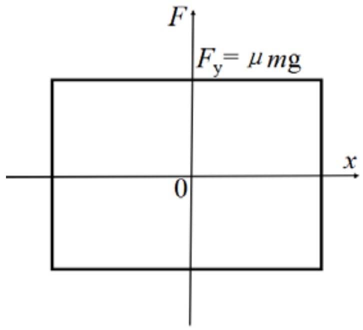

Fig. 3 – Double spherical isolation bearing mechanical model

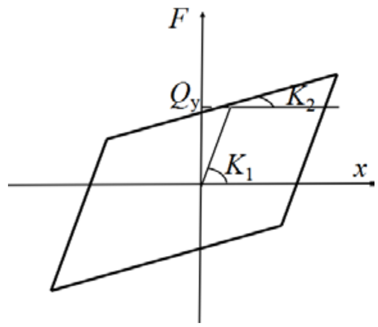

Fig. 4 – LRB mechanical model

2.3 Lead rubber bearing

The LRB has the advantages of good isolation, energy dissipation performance. And it not only support the weight of the upper structure also can provide an elastic restoring force. So it is considered to be an ideal device for bridge isolation. It has been highly valued and widely used in the United States, Japan, New Zealand, Italy and other countries. Some isolated bridges have shown good seismic performance in several earthquakes, which further shows the superiority of the bridge seismic isolation technology and abroad prospects for development[5]. A lot of experiments show that the hysteresis curve of the lead rubber bearing can be expressed by bi-linear model. Wherein the performance parameters are elastic stiffness K_1, yield strength F_y and yield ratio η. (The yield ratio η is equal yield stiffness K_2 divided by elastic stiffness K_1) .

2.4 Working principle of the seismic isolation system

In this paper, double spherical isolation bearings and a LRB was connected in parallel to form new seismic isolation system for high-speed railway simply-supported girder bridge(as show in figure 1). By designing the performance parameters of the new seismic isolation system reasonably, the system can play different roles in the different stages of the pier.

Working stage 1: In the elastic deformation range of the pier, by adjusting the friction coefficient of the double spherical isolation bearings, the double spherical isolation bearings does not slide. The double spherical isolation bearings bear all of the vertical load and provide sufficient lateral stiffness. The LRB is in the free state.

Working stage 2: When the pier enters the elastic plastic deformation stage, the double spherical isolation bearings is sliding. The vertical load on the double spherical isolation bearings is transferred to the LRB. The LRB began to play a major role. The LRB dissipate the seismic energy through elastic plastic deformation and limit the longitudinal displacement of the beam effectively.

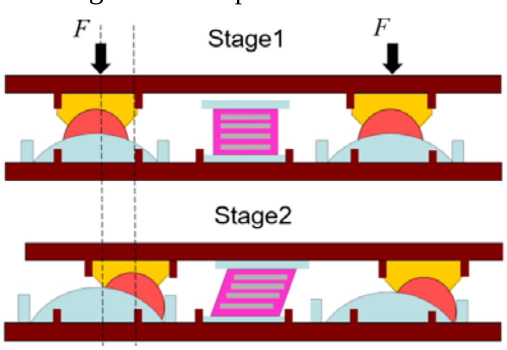

Fig. 5 – Working principle of the new seismic isolation system

Through the above two stages working mechanism, the new seismic isolation system can achieve such a control objective. (1)During the pier in the elastic working stage, by fully playing the seismic performance of the pier, the longitudinal displacement of the beam is prevented. (2)During the pier in the elastic plastic working stage, the hysteretic behavior of the LRB is fully played and the longitudinal displacement of the beam is restricted effectively.

3. Performance parameters optimization

3.1 Bridge structure analysis model

In this paper, the performance parameters of the seismic isolation system are optimized based on Zhang Jiatian bridge in the Changkun high-speed railway simply-supported girder bridge. The bridge span combination of 2×24+13×32+(60+100+60)m. Bridge site category is Ⅲ class venue Seismic fortification intensity is 8 degrees and site characterization cycle is 0.45s. Using high-speed rail span 32m simply supported beam plot typical single pier, computing model is established. The pier cross section shown in figure 6. The pier height is 23.5m, simple box girders span is 32.6 m. Box girder weight 8190.5kN, dead load 184 kN/m. The yield moment of the pier is 67783.386 kN·m, ultimate bending moment is 97148.710 kN·m. Single pier model is shown in figure 7. Consider the case that only seismic waves along the bridge is loaded. The soil - structure interaction, suppose the pier bottom press fastened is not considered in the model.

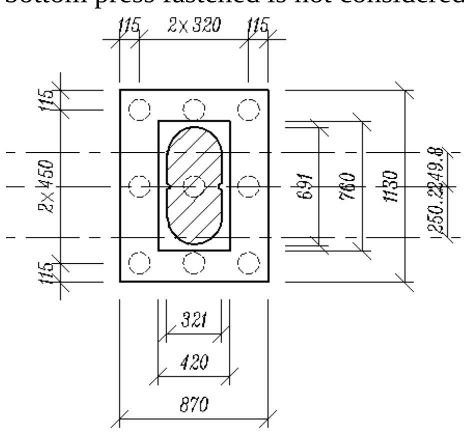

Fig. 6 – The pier-sectional view

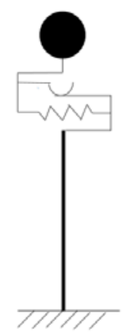
Fig. 7 – Analysis model of single isolated pier

3.2 Determine the size range of seismic isolation system

Before optimizing the performance parameters of the new seismic isolation system, it is necessary to determine the size range of the new seismic isolation system based on the known analytical model parameters. Considering size of the pier sectional as shown in figure 6 and structure of the top section of the pier, it is assumed that 4 new seismic isolation systems are installed at the top of each bridge pier. So the vertical load of each new seismic isolation system will be 1/4 of the vertical load at the top of the bridge pier. It is 3519.6kN. According to the design requirements that vertical compressive strength of the LRB is not more than 10Mpa, we can know that the diameter of each lead rubber is not less than 670mm. Therefore, the diameter of the lead rubber bearing is set to 700mm temporarily.

3.3 Optimization design of the new seismic isolation system performance parameters

3.3.1 Double spherical isolation bearing parameter determination

In the pier elastic working range, the double spherical isolation bearings does not slip. Therefore, according to the critical horizontal earthquake force can be subjected to the bridge pier, the friction coefficient of the spherical seismic isolation bearings is obtained. The friction coefficient is 0.21.

3.3.2 LRB performance parameters optimization

Considering the safety of running vehicles on the high-speed railway simply-supported girder bridge when the earthquake occurs, the performance parameters of LRB is optimized . The LRB performance parameters yield strength Q_y, elastic stiffness K_1 and yield ratio η used as design variables. The maximum bending moment at the bottom of the pier M_{max} is designed as an objective function under the rare earthquake.

Firstly, introduction of seismic isolation system increases the longitudinal displacement of the beam. If left unchecked, it will make the risk of falling girder when design earthquake occurs. So in the process of optimizing design , the maximum longitudinal displacement of the beam D_{max} is taken as the constraint condition to ensure the longitudinal displacement of the beam within a permissible range. Secondly, the maximum shear of the pier F_{max} is taken as constraint condition to ensure that the pier does not yield, when design earthquake occurs. Above all the design parameters optimization problem of the simple supported beam bridge seismic isolation system of the high-speed railway simply-supported girder bridge is described as follows.

Find:	Q_y, K_1, η
To minimize:	$\max\{abs(M(X_i,t))\}$
Subject to:	$\max\limits_{x\in T}\{abs(D(X_i,t))\} \le [D]$
	$\max\limits_{x\in T}\{abs(F(X_i,t))\} \le F_y$
	$X_i^L \le X_i \le X_i^U$

X_i is design variable. T is the duration of the earthquake excitation. $M(X_i,t)$, $D(X_i,t)$ and $F(X_i,t)$ is the bending moment at the bottom of the pier, the longitudinal displacement of the beam, the horizontal load of the pier, respectively, at t time of earthquake excitation, when the design variable is X_i. $[D]$ is the allowable values for the longitudinal displacement of the beam. F_y is the yield shear of piers, in this paper the yield shear of piers is 2915.0kN. X_i^L and X_i^U are the upper limit and the lower limit for the respective design variables, academy of railway sciences experimental data based on LRB's [8], wherein, $X_i^L = [10000kN/m, 100kN, 0.01]$ $X_i^U = [100000kN/m, 5000kN, 1.00]$.

In this study, Sequential Quadratic Programming (SQP) is used to solve the optimization problem of the design parameters of the LRB for a railway simply-supported girder bridge. SQP has the advantages of wide search range and fast convergence. Specific procedures for solving the process shown in figure 8.

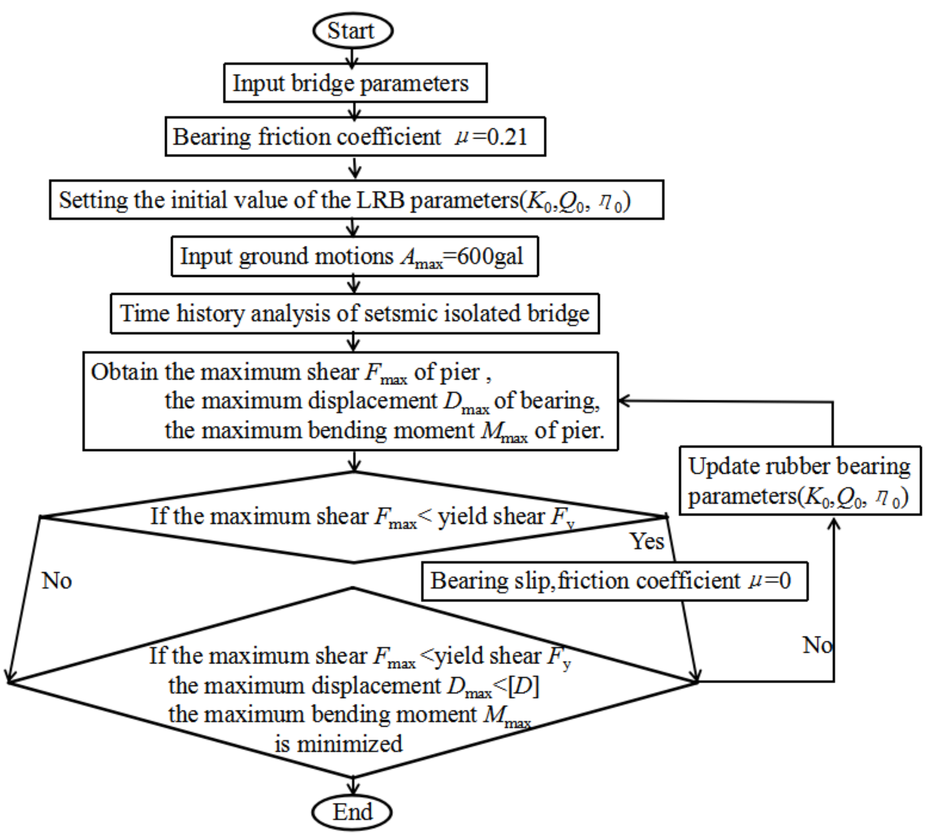

Fig. 8 – Solving optimum design process

In accordance with the requirements of similar site conditions, 7 seismic waves were synthesized(as shown in figure 9). The seismic peak acceleration of each seismic wave is normalized to 600gal to be used as an optimal design input ground motion.

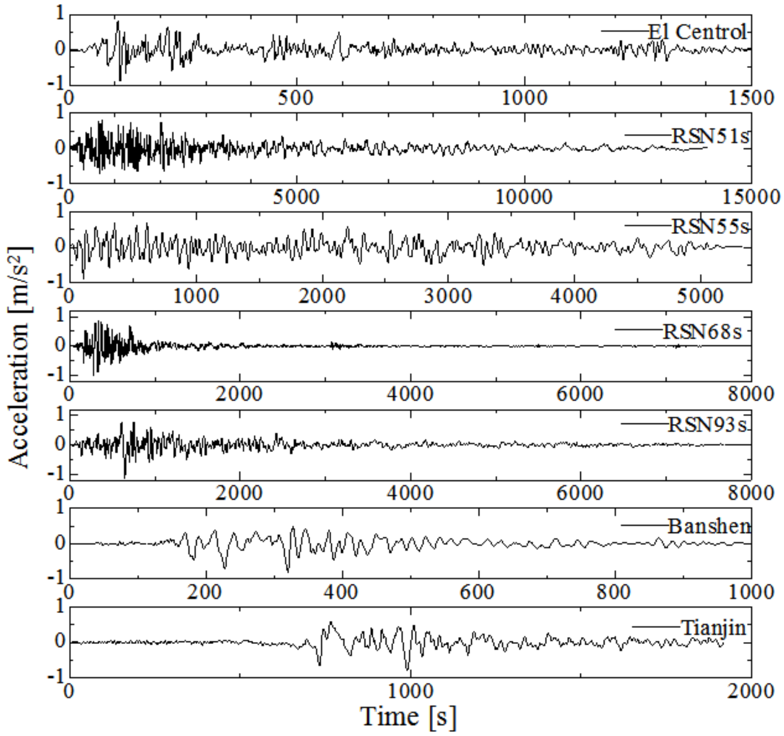

Fig. 9 – Input seismic excitation

3.4 Result analysis

3.4.1 Optimization

Table 2 shows the optimal solution of the performance parameters of LRB and the maximum seismic responses of the isolated bridge under the condition that these optimal solutions are adopted for the performance parameters of LRB. In order to discuss the influence of optimal design on the control effect of the new seismic isolation system, table 2 also shows the initial values of the performance parameters of LRB and the maximum seismic responses of the isolated bridge under the condition that these initial values are adopted for the performance parameters of LRB. The following conclusions can be drawn from the results of table 2. Firstly, the optimal solutions are obtained to satisfy the constraint conditions in the feasible region of the performance parameter of LRB. Secondly, compared with the initial conditions, the optimal design in the following 3 aspects to improve the control effect of the new seismic isolation system. (1)The maximum longitudinal displacement of the bridge is reduced by 54.7%, which is controlled in the allowable deformation range of the LRB.(2) The maximum shear force of the pier is reduced by 30.00%. And the optimal design ensures that the bridge pier will not yield under the 7 seismic waves considered in this paper. (3) The maximum bending moment of the bridge pier is reduced by 30.00%. And thus greatly reduces the possibility of failure of the bridge pier.

3.4.2 Convergence of optimization design

In the optimal design process, the convergence of maximum longitudinal displacement of the beam, the convergence of maximum shear force of the pier and the convergence of 3 optimization design variables are shown in figure 10. As shown in figure 10, the entire search process is shared by 54 steps. The constraint conditions of maximum longitudinal displacement of the beam and the constraint condition of the maximum shear force of the pier always play an effective role in solving the problem. So these two constraints have great influence on the selection of the optimal solution of the LRB. Three design variables of LRB are convergented rapidly and stable after 40 steps of iteration.

Table 1 – Optimization design results

Variables and objective function	The initial value	Optimal solution
Elastic stiffness K_1 (kN/m)	13000.000	26914.000
Yield strength Q_y (kN)	607.500	447.700
Yield ratio η	0.100	0.039
Longitudinal displacement D_{max} (m)	0.607	0.275
Maximum pier Shear F_{max} (kN)	4163.900	2915.250
Maximum pier bending moment M_{max} (kN·m)	97851.570	68508.430

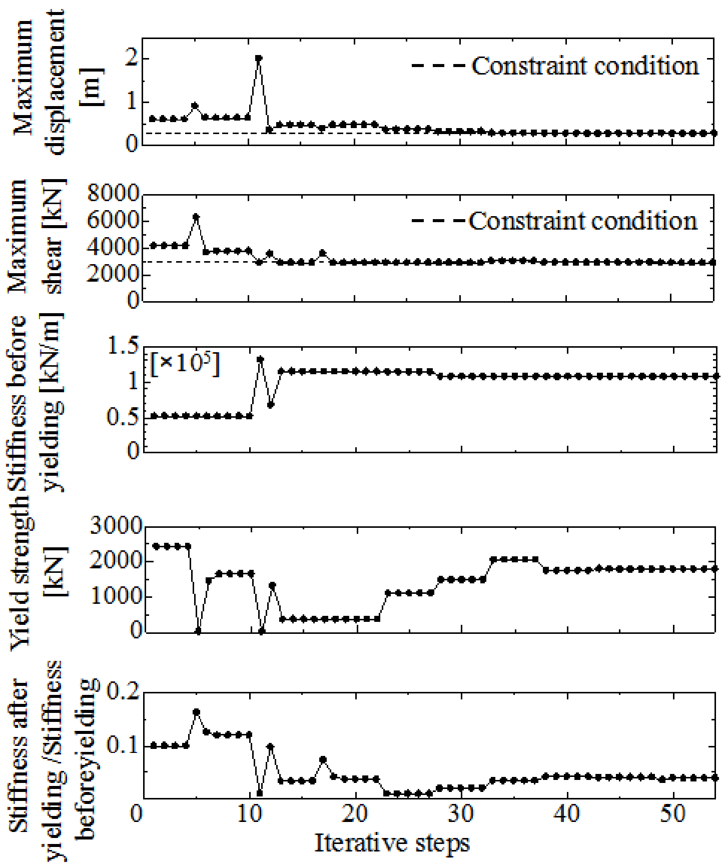

Fig. 10 – Optimal solution iteration

3.4.3 History curves and hysteresis loop

Figure 11 shows the time history curves of maximum longitudinal displacement of the beam and the time history curves of maximum shear of the pier, when El-Centro seismic wave whose peak acceleration is 600gal occurs. Figure 12 shows the the hysteresis curves of the damping force of LRB. In both figures, black lines denote the case of LRB performance parameters using the initial values. Red lines denote the case of LRB performance parameters using the optimal solutions. By comparing the time history curves and hysteretic loops in above two cases as shown in figure 11 and figure 12, we can know that by optimizing performance parameters, the seismic responses of the bridge was reduced effectively, and the damping force of the LRB was reduced by 60.21%. So the optimal design of the performance parameters can give full play to seismic isolation performance of the LRB, and reduce the production cost of the LRB.

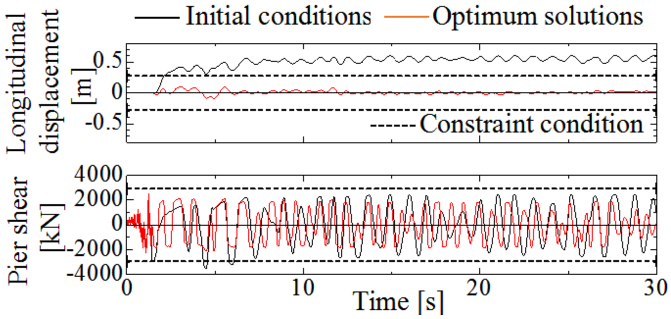

Fig. 11 – Time history curves

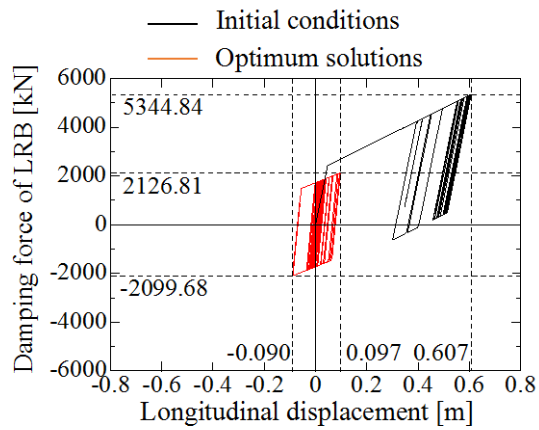

Fig. 12 – Hysteresis loops

4. conclusion

In this paper, a new seismic isolation system is proposed for the simple supported beam bridge of high-speed railway simply-supported girder bridge. Taking an actual high-speed railway simply-supported girder bridge as the research object, the calculation model of single pier of the high-speed railway simply-supported girder bridge is established, and the performance parameters of the new seismic isolation system are optimized. The following conclusion can be obtained by comparing the seismic response of the isolated bridge before the optimization and after the optimization.

(1)The optimal solutions to satisfy the constraint conditions are obtained in the feasible region of the LRB performance parameters for the analysis model of this paper. The optimal design improve the control effect of the new seismic isolation system, and reduce the production cost.

(2)The new seismic isolation system on the seismic responses of high-speed railway simply-supported girder bridge under strong earthquake has good control effect. The new seismic isolation system can reduce the longitudinal displacement of the beam and guarantee the pier not yielding, so that the bending moment at the top of the pier was minimized.

(3)For the seismic isolation design of high-speed railway simply-supported girder bridge, the longitudinal displacement of the beam and the pier shear are the main constraint conditions, which play a major role in the selection of the performance parameters of the seismic isolation system.

(4)Using the SQP algorithm to solve the optimization design model established in this paper, the optimal solution converges quickly and is stable.

5. Outlook

Although it has been proved that the new type of seismic isolation system which was proposed in this paper has a superior seismic isolation effect, it is necessary to carry out the following research works.

(1)Verify the stability of the new type of seismic isolation system under dynamic loads and the realization of the performance objectives by experiments. Discuss the correctness of the mathematical model presented in this paper.

(2)In the practical application, there is a problem of coefficient of friction, which limits the new type of seismic isolation system be wide used in the field of bridge seismic resistance. The friction coefficient of the new isolation system is related to the material properties of the contact surfaces, the pressure of the contact surfaces and the sliding speed. Generally determine the actual bearing friction coefficient only from the measured material under a certain pressure and a certain sliding speed, although the friction coefficient has great influence on the seismic isolated bridges, precise control the friction of the new type of seismic isolation system is almost impossible.

6. Reference

[1] Ji Xiaoyong. Dynamic Response Analysis of High-speed Railway Bridge under Rare Earthquake Action[J]. Highway Engineering. 2012.37(2):176-185.

[2] Buckle I G. Mayes R L. Seismic isolation history: application and performance-a world review[J]. Earthquake Spectra.

1990. 6(2): 181-201.
[3] Guo Lei, Li Jianzhong, Fan Lichu. Research on Seimic Isolation Design gor Long-span Continuous Bridges[J]. China Civil Engineering Journal.2006. 39(3): 81-85.
[4] Wang Li. Analysis of Seismic Isolation Performance of the Lead rubber Bearing Bridge[D]. Beijing:Northern Jiaotong University, 2002.
[5] Fan Lichu, Wang Zhiqiang. Application of Seismic Isolation Technology for Bridge in China[J].Journal of Vibration Engineering.1999, 12(2): 173-181.
[6] Fan Lichu, Yuan Wancheng. Seismic Isolation and Energy Absorption Propertics of Elastomeric Pad Bearing for Bridge[J]. Journal of Tongji University.1989, 17(4):447-455.
[7] Zou Fulin. Engineering Structure Vibration Control[M].Beijing:Seismological Press,1996.
[8] Albert P., Marco M. Seismic isolation of bridges in Italy[J]. Bulletin of the New Zealand National Society for Earthquake Engineering, 1992,25(3):193-202.
[9] Wu Bin. Study on Mechanical characteristic of Lead-rubber Bearing and the response of isolated bridge with the lead-rubber bearing[D]. Beijing:Academy Railway Science.2003.
[10] Skinner R I. Robinson W H, MeVerry G H.(1996). Introduction to Engineering Isolation(Xie Lili,Trans.).Beijing: Seismological Press.