Research on the Design Approach of Displacement Restriction Device of Function-variable Seismic Isolation Bearing of Bidirectional Seismic Isolation Bridge

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SUMMARY:
To promote the application of seismic isolation technology in railroad bridge, based on the high requirement of railroad bridge on the smoothness of the rail, this paper proposes the design concept of displacement restriction under occasional and frequency earthquakes and seismic isolation under rare earthquakes, and it also develops X type mild steel displacement restriction device independently, as well as the design approach to yield strength of this device. Moreover, ANSYS - a finite element analysis software is applied to establish a finite element model of three-span seismic isolation bridge, and the analysis of the displacement restriction function and seismic isolation effect of the seismic isolation bearing with a displacement restriction device is also conducted, proving the validity of the design approach. The analysis result indicates that the displacement restriction device can effectively restrict the displacement of the upper structure of the bridge under occasional and frequency earthquakes; under large earthquake, the displacement restriction device enters into the yield stage and works with the seismic isolation bearing and they achieve good seismic isolation results.

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1. INTRODUCTION

In recent years, many scholars at home and abroad have conducted a lot of researches on the seismic isolation design of bridge seismic isolation, most of which concentrate on the mechanical property analysis of seismic isolation bearing and finite element analysis of dynamic performance of the whole seismic isolation bridge. So the researches into the application of seismic isolation bridge in Railroad Bridge are relatively less. Railroad Bridge has high requirements on the smoothness of the rail, and great displacement in the upper structure will cause great deformation in the rail, seriously affecting the safety of the train operation. If the seismic isolation technology is applied in Railroad Bridge, the displacement of the upper structure of the bridge under the occasional and frequency earthquakes should be restricted. This paper proposes the design concept of displacement restriction under occasional and frequency earthquakes and seismic isolation under rare earthquakes. Currently, seismic isolation bearing mainly includes lead rubber bearing, high damping rubber bearing, friction pendulum rubber bearing, and among them the lead rubber bearing is mostly widely used. The seismic isolation bearing in this paper is lead rubber bearing. If the diameter of the lead core is enlarged to increase the yield strength and initial stiffness of the bearing, it will affect the replacement function of the bearing under rare earthquakes.

This paper intends to adopt easily replaceable mild steel-X type steel sheet as the displacement restriction device, which has the function of displacement restriction under frequent earthquakes and designed earthquakes. The displacement restriction device and lead rubber bearing both enter into the yield stage under the rare earthquake, and they play the role of seismic isolation and energy dissipation. After the rare earthquake, the mild steel displacement restriction device is replaced, and the lead rubber bearing resets automatically. This paper proposes the design approach to displacement restriction device, and also provides the seismic isolation design for a three-span railroad bridge. It has established a finite element model of seismic isolation bridge with a displacement restriction device, a finite element model of seismic isolation bridge without a displacement restriction device, and a finite element model of seismic non-isolation bridge. It also analyzes the seismic response time and proves the validity of the design approach.

2. DESIGN OF DISPLACEMENT RESTRICTION DEVICE

2.1. Restoring Force Model of X-shape Steel Plate Displacement Restrictor

In this paper, the restoring force model of steel plate displacement restrictor is simplified into bilinear intensifying model, and it can be described by bilinear model as shown in Figure 1. Generally, the maximum displacement of a damper is about 20-30 times as the yield displacement. The second stiffness coefficient of steel member is usually 1/30. The calculation of stiffness and damping coefficient respectively adopts equivalent linear method of averaging the probability and amplitude of secant stiffness, damping coefficient, etc. Equivalent damping and stiffness are as follows through formula (1) and (2):

$$c_{eq} = \begin{cases} 0 & d_m \le d_y \\ \dfrac{4(1-\alpha)k_u d_y}{\pi\omega d_m}\left(\dfrac{d_y}{d_m} + \ln\dfrac{d_m}{d_y} - 1\right) & d_m > d_y \end{cases} \tag{1}$$

$$k_{eq} = \begin{cases} k_u & d_m \le d_y \\ \alpha k_u + (1-\alpha)k_u \dfrac{d_y}{d_m}\left(1 + \ln\dfrac{d_m}{dy}\right) & d_m > d_y \end{cases} \tag{2}$$

In the formula, k_u , d_y and α are the initial stiffness, yield displacement and second stiffness coefficient, as shown in Figure 1.

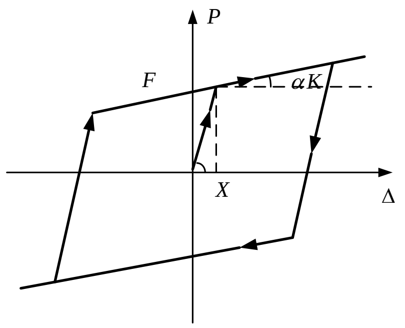


Figure 1. Calculation model of X shape steel plate constitution relationship

Seen from formula (1), when the displacement of X-shape steel plate displacement restriction device is less than or equal to its yield displacement, the displacement restriction device only adds stiffness to the bridge structure rather than damping. When the displacement of the steel device is more than its yield displacement, the added damping increases as the displacement increases; the relevant response curve gradually falls, equivalent stiffness decreases and the cycle enlarges.

2.2. Design Approach to the Yield Strength of the Displacement Restrictor

To ensure the mild steel displacement restrictor will yield under rare earthquake, and function displacement restriction under occasional and frequency earthquakes, and also to ensure the seismic isolation of lead rubber bearing, the response spectrum method is applied to design the yield strength of the displacement restrictor.

When the time-history analysis is conducted, in view of the different results of time-history analysis when each seismic wave is input, Code for Seismic Design of Buildings stipulates that the effect size should be estimated according to the calculation results of small sample size. Through the statistics analysis of time-history analysis results when different structure types are input into the large amount of earthquake acceleration record, if no less than 2 actual records and 1 manual simulate acceleration time-history curve are input, the reliability that the average earthquake effect size is not less than the average of large sample size is over 85%, and the oversize is conservative. The so-called "statistical consistency" refers to that when the average earthquake impact coefficient curve is compared to the earthquake impact coefficient curve by response spectrum method; the difference at each cycle point is less than 20%. The average bottom shear is generally not less than 80% of the calculation result by response spectrum method. Each earthquake wave will not get a result less than 65%. To input the earthquake wave of rare earthquake which meets the standards, and to ensure that the steel plate displacement restrictor of combined bearing can yield, in design, this paper reduces the shear size by 35% under the rare earthquake by response spectrum method and uses it as the yield load for steel plate displacement restrictor.

The specific calculation process is as follows:

1) In the seismic bridge with a combined bearing with a displacement restriction device, suppose natural vibration period corresponding to the initial elastic stiffness lies in the platform of the response spectrum curve, the maximum seismic force $Q(1)$ is obtained. Under the seismic force, the seismic isolation device is in the elastic stage. If the yield displacement of the steel plate displacement restrictor is known, then the minimum elastic stiffness of the combined bearing $k(1)$ (the combined stiffness of lead rubber bearing and steel plate displacement restrictor) is obtained, and through the weight of upper structure and the elastic initial stiffness, the initial value $t(1)$ of the natural vibration period is obtained.

2) The natural vibration period $t(i)$ of the structure is obtained, and through the response spectrum curve, the seismic force $Q(i)$ is obtained.

3) The yield displacement of the steel plate displacement restrictor is known, the elastic stiffness $k(i)$ is obtained. Through the weight of the upper structure, the natural vibration period $t(i+1)$ of the structure can be obtained.

4) Check whether the seismic error $\frac{Q(i+1)-Q(i)}{Q(i)} \le \varepsilon$ meets the requirements, if not, the calculation should be repeated through step 2) and 3).

5) Reduce the seismic force by 35%, and obtain the yield shear of each bearing according to the stiffness distribution of each combined bearing.

6) Subtract the shear force of lead rubber bearing corresponding to yield displacement of steel plate displacement restrictor from the yield shear force of each bearing, and then the design size of the yield strength of steel plate displacement restrictor is obtained.

Figure 2 shows the design procedure of the yield strength of steel plate displacement restrictor.

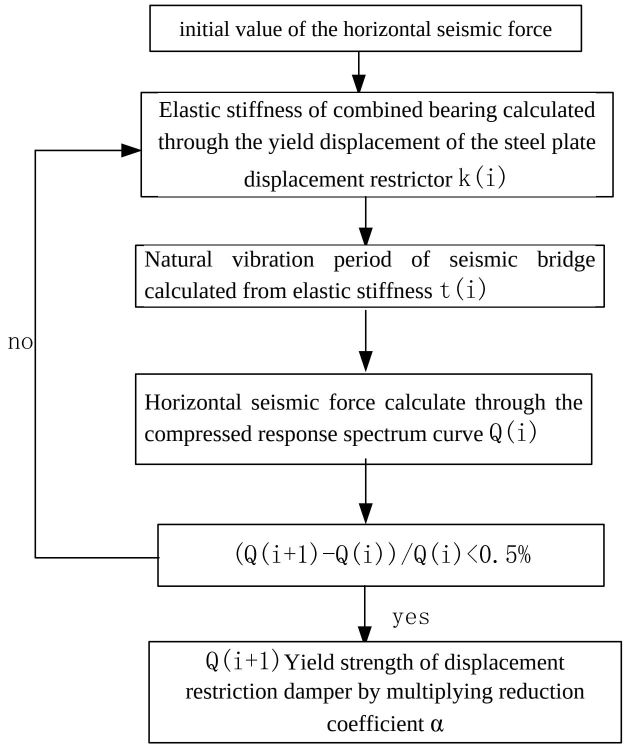


Figure 2. Design procedure of displacement restrictor

3. SEISMIC TIME HISTORY RESPONSE ANALYSIS

3.1. Bridge Model

This paper chooses a pre-stressed concrete three-span railroad bridge of continuous beam as the bridge model. Before the seismic isolation design, 2# bridge pier bearing uses hinged connection (vertical sliding at other piers). Each abutment has 2 lead rubber bearing (LRB). The piers are numbered 1#, 2#, 3# and 4# from left to right. This bridge is structured with seismic isolation design. See Figure 3 for the seismic isolation bridge model.

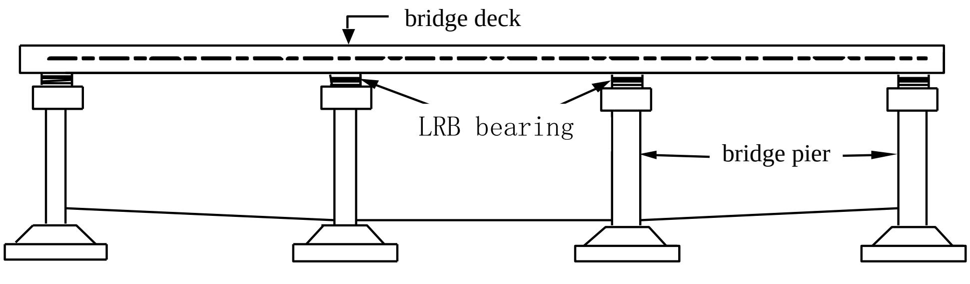


Figure 3. Sketch of seismic isolation bridge

3.2. Combined Seismic Isolation Bearing

This paper uses the previous research results as the reference, and when conducting the infinite element analysis of the bridge, selects $K_s = K_1 / 30$, and $d_s = 20d_y$. See Table 1 for the parameters of the X-shape steel plate displacement restrictor through design. The mechanical model of lead rubber bearing and displacement restrictor is simplified into a bilinear model.

Table1. Parameters of X-shape steel plate deform displacement restrictor

Parameter	Yield displacement (mm)	Yield strength (kN)	Limit position (mm)	Limit strength (kN)	Elastic stiffness (N/m)
Number	3	396.35	40	594.53	1.32e8

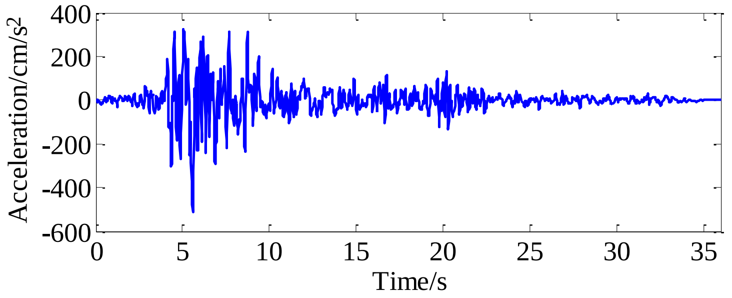
See Table 2 for parameters of lead rubber bearing of seismic isolation bridge.

Table 2. Parameters of LRB

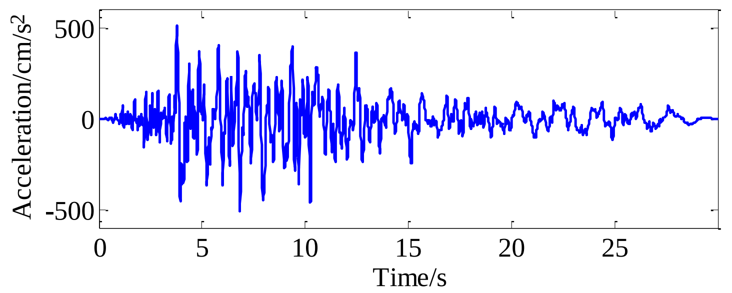
Parameter	Number	Parameter	Number
Seismic isolation period (s)	1.5	Initial stiffness（N/m）	1.08e7
Seismic isolation damping	0.20	Post-yielding stiffness (N/m)	1.08e6
Yield strength (N)	4.50e4		

3.3. Seismic Wave

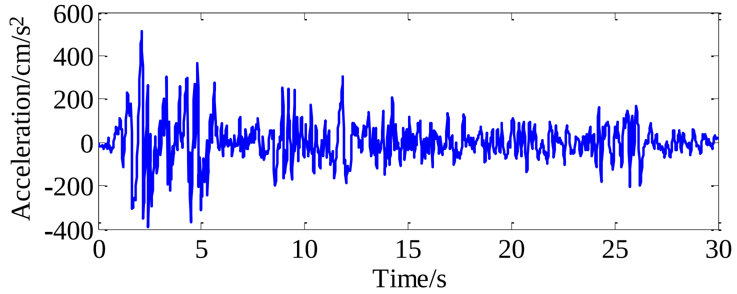
The bridge is located in Category Ⅱ site, and the seismic intensity is 8. Three seismic records representing Category Ⅱsite are selected. The three seismic waves selected are CAPEMENDRIO Wave (C Wave), NORTHRGLE Wave (N Wave) and ELCENTRO Wave (E Wave). Figure 4 shows time histories of seismic waves. Table 3 is the parameters selected seismic waves.



a) C wave



b) N wave



c) E wave

Figure 4. Seismic waves in the analysis

Table 3. Parameters of selected seismic waves

Name of the seismic wave	Medium seismic peak (cm/s2)	Large seismic peak (cm/s2)	Time step（s）	Duration（s）
C			0.02	36
N	300	510	0.01	29.99
E			0.02	30

3.4. Analysis of the Restricting Effect of the Displacement Restriction Device

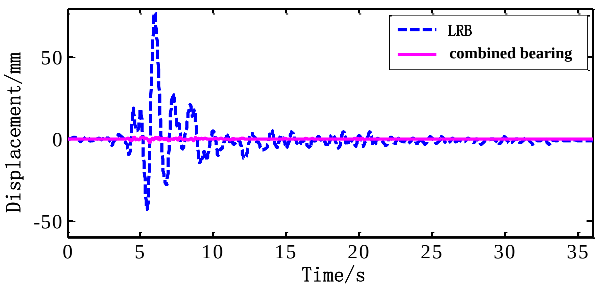
Three seismic waves are selected to conduct the time-history response analysis under the designed earthquakes on the seismic isolation bridge models with lead rubber seismic isolation bearing and combined bearing respectively. The response peaks of relative displacement of beating of each bridge model under designed earthquakes are shown in Table 4. Seen from the data of the table, when the mild steel displacement restrictor is applied, under the designed earthquakes, the displacement of the upper and lower connection plates of the bearing is less than 2 mm, and the restricting rate of the relative displacement of the bearing is over 95.36%.

Table 4. Relative displacement peak value of model bearing of seismic isolation bridge under designed earthquakes

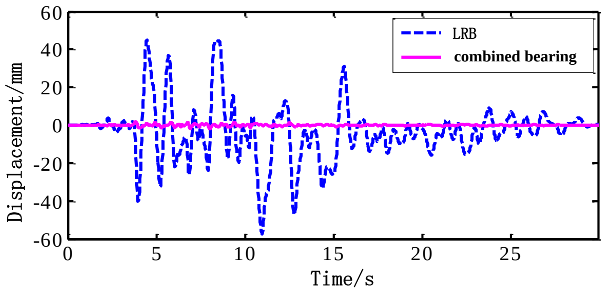
Bearing number	LRB model(mm)			Combined bearing model (mm)			Displacement restriction rate			
	C wave	N wave	E wave	C wave	N wave	E wave	C wave	N wave	E wave	Average
2#	77.70	57.20	43.10	2.00	1.90	2.00	97.43%	96.68%	95.36%	96.49%
4#	77.70	57.20	43.10	2.00	1.90	2.00	97.43%	96.68%	95.36%	96.49%

Table 5. Relative displacement peak value of model bearing of seismic isolation bridge under rare earthquake

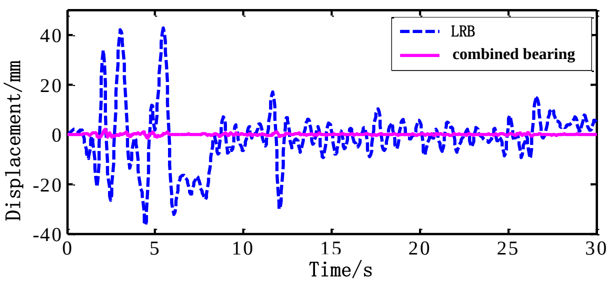
Bearing number	LRB model (mm)			Combined bearing model (mm)			Displacement restriction rate			
	C wave	N wave	E wave	C wave	N wave	E wave	C wave	N wave	E wave	Average
2#	146.00	105.70	96.90	12.90	10.20	14.70	91.16%	90.35%	84.83%	88.78%
4#	146.00	105.70	96.90	12.90	10.20	14.70	91.16%	90.35%	84.83%	88.78%



a) Relative displacement time history curve under C



b) Relative displacement time history curve under N



c) Relative displacement time history curve under E

Figure 5. Relative displacement time history curve under designed earthquake

The relative displacement time-history curve of the bridge models with lead rubber seismic isolation and with combined bearing is shown in Figure 5. Seen from the figure, the maximum displacement of LRB reaches 77.70 mm, causing great deformation of the rail structure vertically, increasing the longitudinal force of the rail and easily causing the instability and damage to the rail. Greater longitudinal displacement and vertical load will function together to cause the vertical displacement of the bearing; horizontal displacement and vertical displacement will intensify the non-smoothness of the rail, seriously affecting the safety of train operation. After the X-shape steel plate displacement restrictor is used, the relative longitudinal displacement of the bearing fluctuates within 2mm under designed earthquakes, so the restrictor functions quite well.

Figure 5 shows the displacement response peak value of seismic isolation models with LRB and combined bearing under rare earthquakes. See from the data of the figure, the X-shape displacement restrictor effectively reduces the displacement of the bearing under rare earthquakes, and also plays a certain function of displacement restriction.

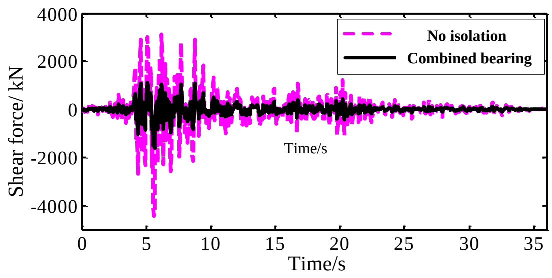
3.5. Seismic Isolation Effect Analysis of Combined Seismic Isolation Bearing

This paper conducts a comparative analysis of the seismic isolation effect of seismic non-isolation bridge model and seismic isolation bridge model with combined bearing. Figure 6 shows maximum value of the pier bottom shear force and bending moment of seismic non-isolation bridge model and combined seismic isolation bridge model under the above 3 seismic waves. For the seismic non-isolation bridge model, the seismic force will be solely undertaken by 2# bearing bridge pier. After the seismic isolation design, the seismic force is evenly undertaken by each pier, making the structure load more appropriate. The average seismic reduction of pier bottom shear force of 2# bridge pier reaches 69.77%, and the average seismic reduction of pier bottom bending moment reaches 69.31%.

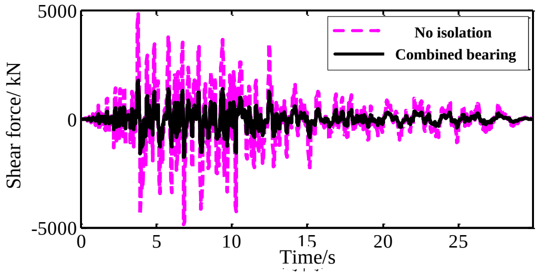
Figure 6a)~f) show the time-history curve of shear force and bending moment of 2# bridge pier bottom under the above selected seismic waves. The figure shows that the seismic isolation bearing with displacement restricting devices functions quite well under the rare earthquakes.

Table 6. Peak value of shear force and bending moment of pier bottom

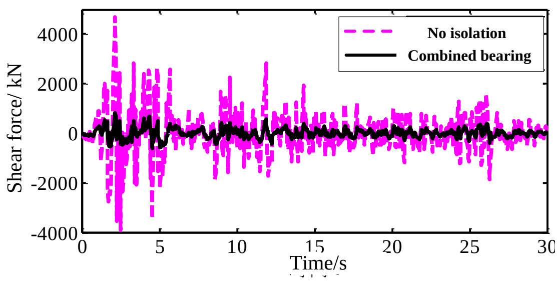
	Seismic wave	Shear force	Bending moment
Seismic non-isolation bridge	C wave	4.43E+06	3.59E+07
	N wave	4.86E+06	4.18E+07
	P wave	4.69E+06	3.73E+07
Seismic isolation bridge with combined bearing	C wave	1.61E+06	1.10E+07
	N wave	1.80E+06	1.37E+07
	P wave	8.24E+05	1.10E+07
Seismic reduction rate	C wave	63.77%	69.56%
	N wave	63.10%	67.69%
	P wave	82.45%	70.69%
	Average	69.77%	69.31%



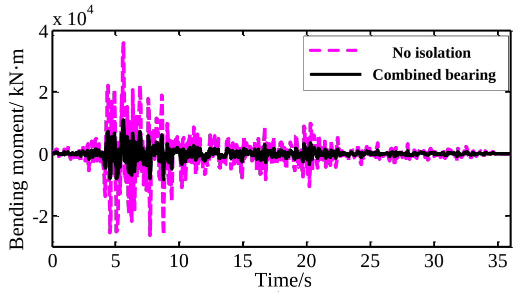
a) Shear force time history under C



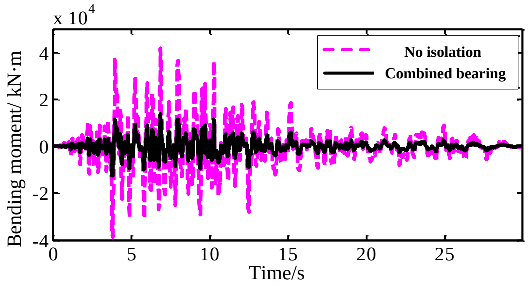
b) Shear force time history under N



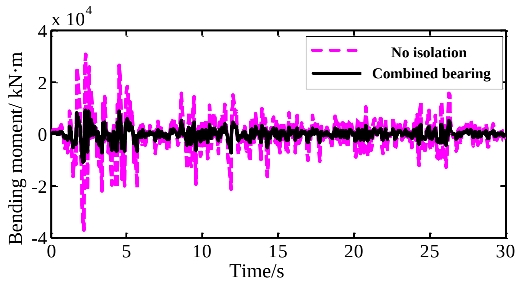
c) Shear force time history under E



d) Bending moment time history under C



e) Bending moment time history under N



f) Bending moment time history under E

Figure 6. Comparison of reaction force of 2# bearing with and without seismic composite bearing

4. CONCLUSION

Through the time-history analysis of infinite element model of seismic isolation bridge, the following conclusions can be drawn:

(1) The displacement restriction device based on the response spectrum method in this paper can keep the elastic state of lower displacement restriction device and LRB under designed earthquakes, and the device functions well. Under rare earthquakes, the restrictor will enter into the yield stage before LRB, and the combined seismic isolation bearing plays the function of seismic isolation and energy dissipation.

(2) Mild steel displacement restricting device can provide larger yield stiffness and certain yield strength under frequent earthquakes and designed earthquakes, effectively restricting the relative displacement of bearing. The small stiffness after yield and the strong deformation ability can have the function of energy dissipation, effectively reducing the displacement of the upper structure of the bridge under rare earthquakes.

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