SHAKETABLE TEST OF SEISMIC ISOLATION STRUCTURE BASED ON SMA WIRE-LAMINATED RUBBER COMBINED BEARINGS

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ABSTRACT:

Aiming at the low horizontal lateral stiffness and restoring force, taking advantage of hyperelastic property of shape memory alloys (SMA for short), a new type of SMA wire-laminated rubber combined bearings is developed by fixing SMA wire diagonally around conventional laminated rubber bearings. Through comparison test on seismic simulation shaketable, analysis is made on effects and rules of displacement amplitude of isolation layer on seismic isolation basic parameters of SMA wire-laminated rubber combined bearings such as unit cycle energy consuming, equivalent horizontal stiffness, maximum restoring force, and equivalent damp ratio. Favorable seismic isolation property of SMA wire-laminated rubber combined bearings is verified.

KEYWORDS: SMA wire-laminated rubber combined bearings, seismic isolation structure, shaketable test, horizontal shear deformation, restoring force

1. INTRODUCTION

For structure seismic isolation, the most widely used isolation device are conventional laminated rubber bearings and lead-rubber bearings [1]. Conventional laminated rubber bearings overcome shortcomings of rubber such as small vertical stiffness, low stability under horizontal loads. But due to insufficient energy dissipation of rubber, bearings instability tends to occur caused by excessive deformation of seismic isolation layer. Rubber-lead bearings have strong energy dissipation capacity and large damp force, which results in better seismic isolation. However, lead cannot recover its original shape after deformation and thereby reduce the self-recover capacity of lead-rubber bearings [2-8]. According to provisions of new code in China, the maximum allowable shear deformation of laminated rubber bearings should be no more than 0.55D (effective diameter of laminated rubber bearings)[9]. But the actual shear deformation is generally larger than 0.55D, and the bearings may not recover its original position [10]. Nevertheless, taking advantage of hyperelastic property of shape memory alloys (SMA for short), SMA wire is fixed diagonally around conventional laminated rubber bearings as supplement of laminated rubber bearings restoring force, which help bearings recover its original position[11]. The author develops a new type of SMA wire-laminated rubber combined bearings. Through shaketable test results analysis of the seismic isolation structure, building seismic isolation theory is perfected. Theoretical fundamentals and technical support are provided for engineering design. It has significant scientific value and applying perspectives.

2. EXPERIMENTAL TESTS

The test was conducted in seismic simulation shaketable laboratory in engineering mechanics institute of China seismic bureau. Three identical specimens were fixed with the shaketable board by high-strength bolts. Dynamic test of one-way relatively horizontal large displacement between the bearing top and the bottom under constant vertical loads was carried out, as shown in figure1. The constant vertical loads were realized by putting clump weight uniformly on the specimen top. The specimen and the clump weight were connected firmly by epoxy

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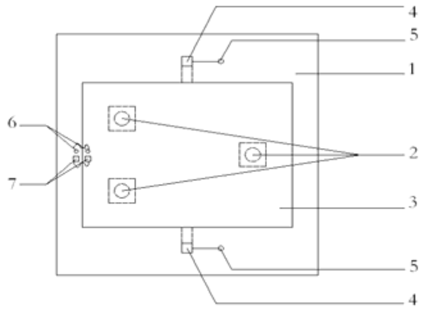
resin. Sensors and SMA wire-laminated rubber combined bearing layouts are shown in figure2. Experimental operating modes are shown in table 2.1.

Figure 1 SMA wire-laminated rubber combined bearing



1.Shaketable board 2.Rubber bearing 3.Reinforced concrete clump weight 4.Relative displacement sensors 5.Fixed end of relative displacement sensors and table-board 6.Absolute displacement sensors 7.Absolute acceleration sensors

Figure 2 Diagrammatic drawing of sensors layout

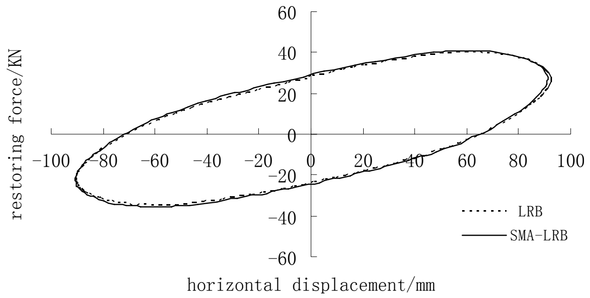
Table 2.1 Operating modes

operating modes	Amplitude of bearing displacement（mm）	SMA elongation（mm）	SMA elongation rate（%）
I	90（0.45D）	0	0
II	100（0.5D）	10	2.33
III	110（0.55D）	20	4.65
IV	120（0.6D）	30	6.98
V	126（0.63D）	36	8.37
VI	141（0.705D）	51	11.86

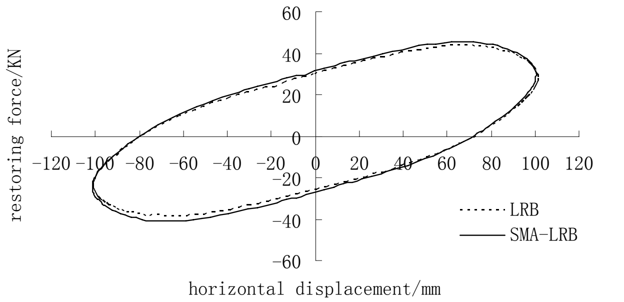
3. EXPERIMENTAL RESULTS AND ANALYSIS

3.1. Experimental Results

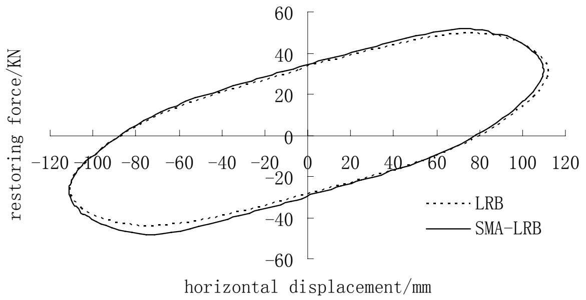
The experimental data were from six different channels of data acquisition, with acquisition time of 138.25 s. the experimental data were exported directly in the form of voltage from each sensor. Experimental results can be computed through sensitivity of each sensor and dynamic equations, as shown in figure 3. According to experimentally measured F-X curves of two bearings under different operating modes, mechanical parameters of the bearing such as unit cycle energy consuming, equivalent horizontal stiffness, maximum restoring force, and equivalent damp ratio can be calculated through numerical methods, as shown in figure 3. Mechanical parameters of the two bearings under different operating modes are shown in table 3.1.



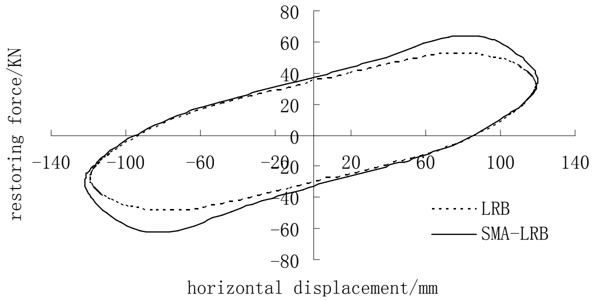
(a) F-X curve of different bearings in condition Ⅰ



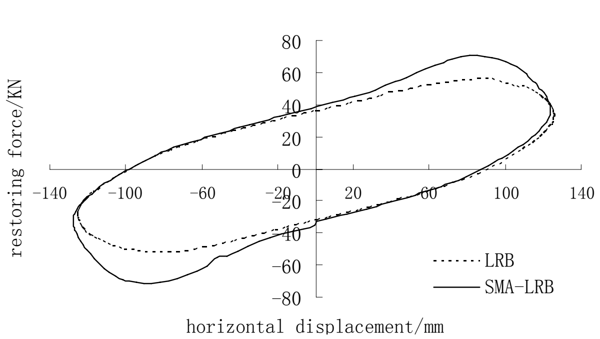
(b) F-X curve of different bearings in condition Ⅱ



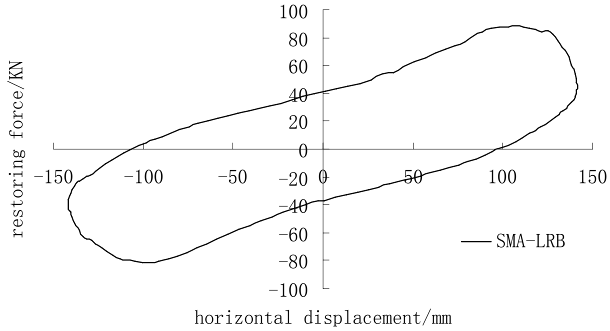
(c) F-X curve of different bearings in condition Ⅲ



(d) F-X curve of different bearings in condition Ⅳ



(e) F-X curve of different bearings in condition Ⅴ



(f) F-X curve of different bearings in condition Ⅵ

Figure 3 F-X curves of two bearings for different operating modes

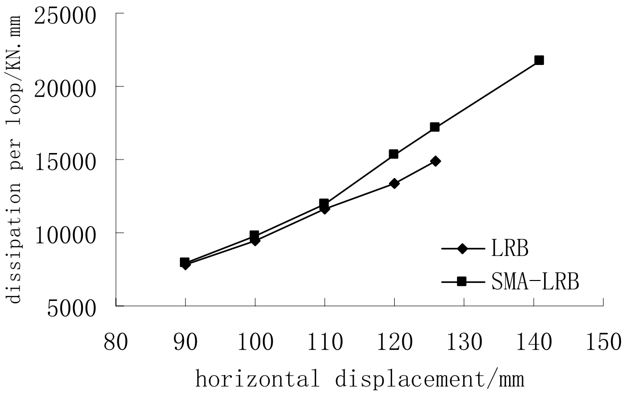


Figure 4 Curve of dissipation per loop

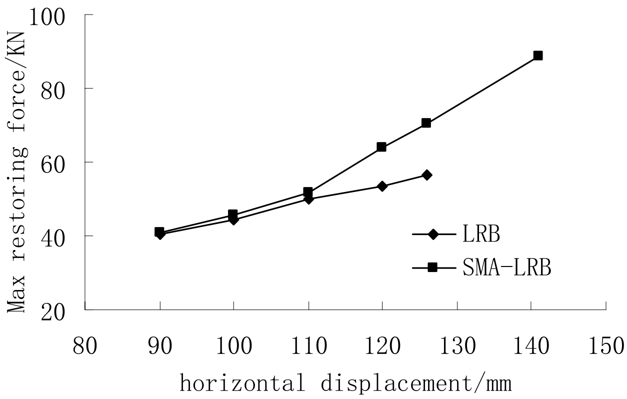


figure 5 Curve of max-restoring force

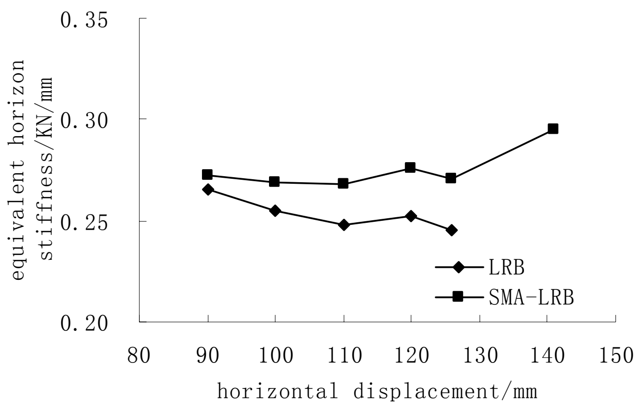


Figure 6 curve of equivalent horizon stiffness

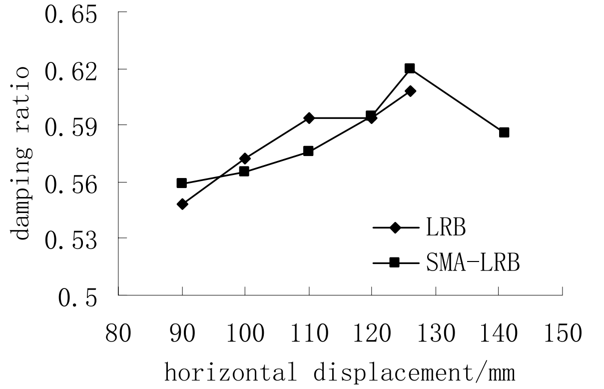


figure 7 curve of equivalent damping ratio

Table 3.1 Mechanical parameters of the two bearings for different operating modes

		I	II	III	IV	V	VI
unit cycle energy dissipation E	Conventional rubber bearing	7833.9	9485.8	11634.9	13371.4	14870.3	
	SMA combined bearing	7922.8	9787.4	11953.5	15294.9	17130.6	21766.3
	rate of change(%)	1.13	3.18	2.74	14.38	15.2	
maximum restoring force *F*	Conventional rubber bearing	40.56	44.14	49.98	53.30	56.67	
	SMA combined bearing	40.88	45.46	51.72	64.02	70.39	88.50
	rate of change(%)	0.7	3.0	3.50	20.1	24.21	
equivalent horizontal stiffness *K*	Conventional rubber bearing	0.265	0.255	0.248	0.252	0.245	
	SMA combined bearing	0.272	0.269	0.268	0.276	0.271	0.295
	rate of change(%)	2.64	5.49	8.06	9.52	10.61	
equivalent damp ratio ξ	Conventional rubber bearing	0.548	0.572	0.594	0.594	0.608	
	SMA combined bearing	0.559	0.565	0.576	0.595	0.620	0.586

3.2. Results Analysis

(1) It can be seen from figure 4 that as the displacement amplitude increases, unit cycle energy dissipation of conventional rubber bearing and SMA wire-laminated rubber combined bearing both increases, with the latter increasing more obviously. The main reason is that when SMA wire acts as energy dissipation material, its unit cycle energy dissipation added on the bearing increases greatly as the displacement amplitude increases. Therefore, when unit cycle energy dissipation of the SMA wire and laminated rubber bearing adds together, its increase curve seems more obvious.

(2) It can be seen from figure 5 that when displacement amplitude of the rubber bearing reaches 90 mm, i.e. before SMA wire involving in working state, restoring force and area of hysteretic curve of conventional rubber bearing and SMA wire-laminated rubber combined bearing are almost the same. When the relative horizontal displacement of the rubber bearing is 100mm, 110mm, 120mm, and 126mm, respectively, restoring force provided by SMA wire accounts for 3%、3.5%、20.1% and 24.2% of the total restoring force, respectively. Thus when SMA wire is in working state, the restoring force of SMA wire-laminated rubber combined bearing increases nonlinearly, showing property of “hard spring”.

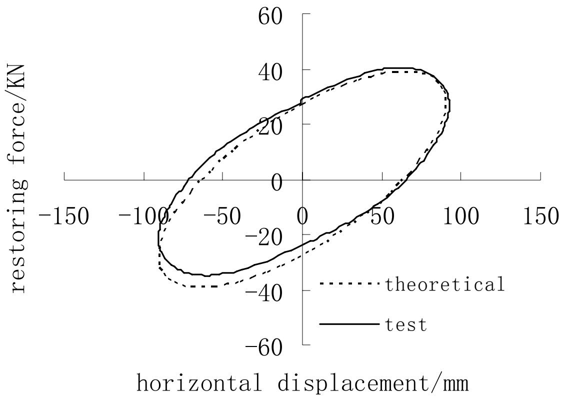
(3) It can be seen from figure 6 that under large deformation, as the displacement amplitude increases, equivalent horizontal stiffness of conventional rubber bearing and SMA wire-laminated rubber combined bearing decreases. However, when displacement amplitude of both is larger than 0.55D, equivalent horizontal stiffness is increasing again, which is caused by stiffness hardening of the rubber bearing. When displacement

amplitude reaches 0.6D, equivalent horizontal stiffness tends to decrease, whose reason is the yielding approaching of the rubber bearing. After that, equivalent horizontal stiffness of SMA wire-laminated rubber combined bearing improves greatly. Since SMA wire strain is larger than 8%, obvious stiffness improvement results in the total stiffness improvement of SMA wire-laminated rubber combined bearing. As a whole, equivalent horizontal stiffness of SMA wire-laminated rubber combined bearing is obviously larger than that of conventional rubber bearing. The main reason is that when displacement amplitude of the bearing reaches 90mm, SMA wire has exceeded its original length, which results in the increase of partial stiffness when SMA wire works together with conventional rubber bearing. Thus, equivalent horizontal stiffness of SMA wire-laminated rubber combined bearing increases.

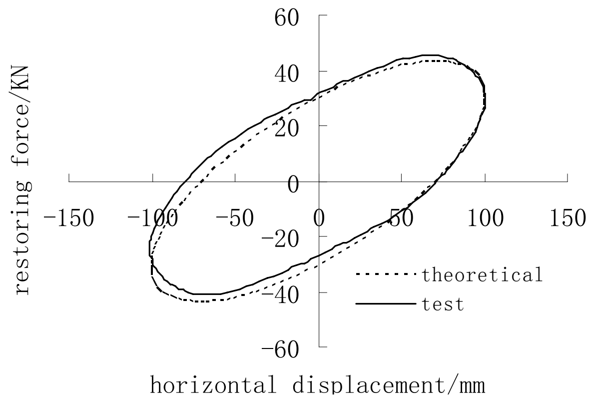
(4) It can be seen from figure 7 that as the displacement amplitude increases, equivalent damp ratio of conventional rubber bearing and SMA wire-laminated rubber combined bearing increase. Since as shear deformation increases, shear stiffness decreases gradually and its energy dissipation capacity improves. When displacement amplitude reaches 130mm, equivalent damp ratio of SMA wire-laminated rubber combined bearing decreases greatly, which is caused by the increase of equivalent horizontal stiffness of SMA wire-laminated rubber combined bearing.

4. COMPARATIVE ANALYSIS BETWEEN EXPERIMENTAL AND THEORETICAL VALUES

Computational procedure is programmed according to the above restoring force model of SMA wire-laminated rubber combined bearings. Comparison is made between experimental values and theoretical values. Results are shown in figure 8 and table 4.1.



(a)



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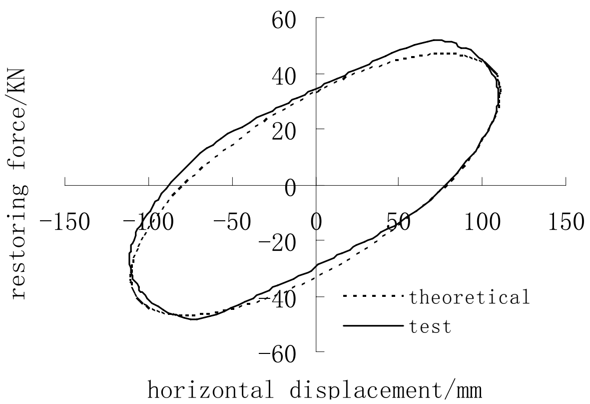

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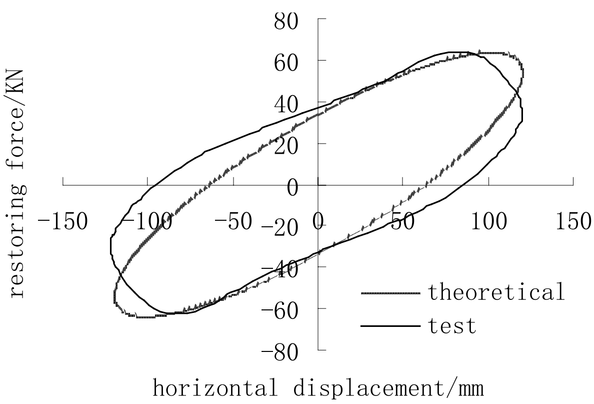
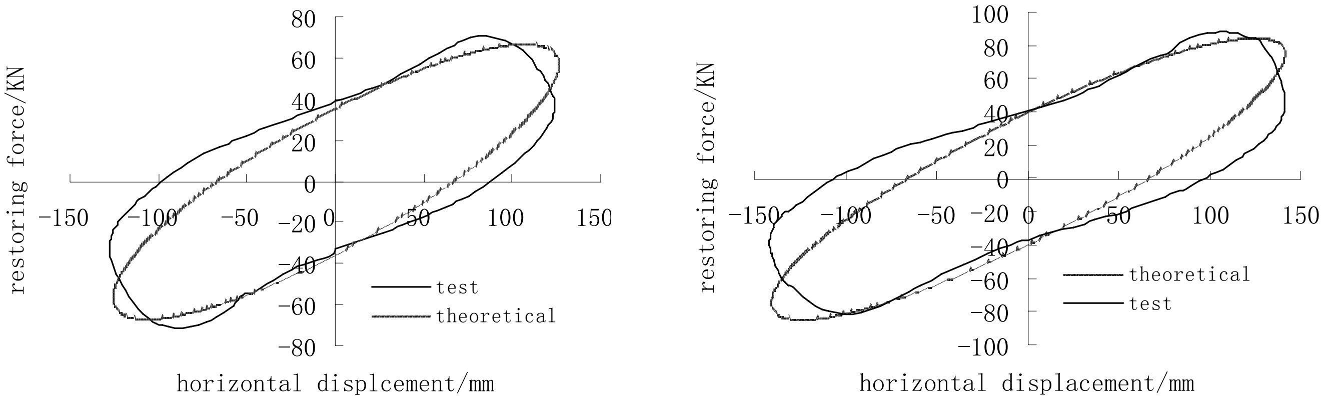


(d)



(e) (f)

Figure 8 Comparison between theoretical and experimental values of restoring force of the combined bearing for different operating modes

Table 4.1 Mechanical parameters comparison for different operating modes

		Ⅰ	Ⅱ	Ⅲ	Ⅳ	Ⅴ	Ⅵ
unit cycle energy dissipation E	Theoretical value	8013.9	9663. 5	11683.3	14203.3	15418.3	20036. 6
	Experimental value	7922.8	9787.4	11953.5	15294.9	17130.7	21766.3
	Error ratio（%）	1.14	1.27	2.26	7.14	10	7.95
maximum restoring force F	Theoretical value	38.83	43.14	46.67	61.32	64.08	81.75
	Experimental value	40.88	45.46	51.72	64.02	70.39	88.50
	Error ratio（%）	5.03	5.11	9.78	4.22	8.96	7.63
Equivalent horizontal stiffness K	Theoretical value	0.307	0.302	0.30	0.271	0.291	0.301
	Experimental value	0.272	0.269	0.268	0.276	0.271	0.295
	Error ratio（%）	11.4	10.9	10.67	1.85	6.87	1.99
equivalent damp ratio ξ	Theoretical value	0.513	0.488	0.496	0.581	0.531	0.533
	Experimental value	0.559	0.565	0.576	0.595	0.620	0.586
	Error ratio（%）	8.23	13.62	13.89	2.35	14.35	9.04

Looking at the comparison between experimental and theoretical curves, the two compares well. Comparative analysis between theoretical and experimental values in table 3 shows that the maximum difference of hysteretic curve area between experimental and theoretical values is 10%; the maximum difference of maximum restoring force is 9.78%; the maximum difference of equivalent horizontal stiffness is 11.4%; the maximum difference of equivalent damp ratio is 14.35%. As a whole, experimental and theoretical values compare fairly well.

5. CONCLUSIONS

(1) Taking advantage of hyperelasic property of shape memory alloy wire, SMA wire was added into conventional laminated rubber bearings and SMA wire-laminated rubber combined bearings was made. It can offset limitations of rubber bearings such as hard to recover automatically, small energy dissipation capacity, and insufficient restoring force providing. It has favorable seismic isolation property.

(2) Through shaketable test of SMA wire-laminated rubber combined bearings, it was verified that when large horizontal displacement of SMA wire-laminated rubber combined bearings occurred in rare earthquakes, it could provide greater restoring force and damp and it was more advantageous for preventing the earthquake acting force for the above structure, and automatic recover of the above structure after strong earthquake.

Experimental tests verified that the horizontal displacement amplitude of SMA wire-laminated rubber combined bearings could be 1.57 times that required in conventional rubber bearings code and still work as usual. It confirmed validity of theoretical analysis for SMA wire-laminated rubber combined bearings.

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