Research on Isolation Performance of Composite Rubber Bearing Bridges

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Abstract

The damage survey of Wenchuan Earthquake shows that medium-to-small-span bridges supported by laminated rubber bearings suffered from excessive displacement for bearing sliding, but commonly used bearings with drawbacks like high economic costs or complex manufacturing, are not suitable for these bridges. Thus, this paper proposes a new type of rubber bearing, Composite Rubber Bearing (CRB), basing on the relationship between force and displacement, which is aimed to make up for the shortcomings of common or new type seismic isolating bearings and to improve the earthquake resistance performance of medium-small span bridges.

The cross section of CRB is a combination of laminated rubber bearing and Teflon sliding bearing, which can be named laminated part and sliding part respectively. The working principle is that sliding part can reduce the horizontal stiffness effectively while laminated part can provide the elastic restoring force, so reaching to the larger displacement ability and a higher energy dissipating capacity of bearings.

To research the seismic isolating performance of CRB, samples were designed and manufactured. Mechanical experiments on vertical stiffness, horizontal equivalent stiffness and quasi-static were done. Results of vertical stiffness tests proved that the composite cross section had little effect on the vertical bearing capacity. The horizontal equivalent stiffness tests showed the relatively low horizontal stiffness and high energy dissipating capacity of CRB compared with the common seismic isolation bearings with similar size. The hysteretic curves under different shear strains were plotted according to the results of quasi-static tests and the hysteretic model of CRB was derived further basing on design concept.

Additionally, according to the hysteretic model, finite element models of simply supported bridges were established to study the seismic isolating performance of CRB bridges compared with laminated rubber bearings bridges. The results showed that under earthquakes, CRB bridges, with a longer nature vibration period and larger damping ratio, had larger displacement ability and the bending moments in piers were reduced effectively.

Therefore, CRB is especially suitable for medium-to-small-span bridges for its simple structure and low economic cost and obvious seismic isolating ability.

Keywords: Composite Rubber Bearing, seismic isolation of bridges, quasi-static tests, hysteretic model of bearings, finite element modelling

1. Introduction

In past 40 years, a mass of bridges have been built in China and most of them are medium-to-small-span highway bridges, usually equipped with laminated rubber bearings for evenly distributing lateral force to each pier as well as for the economic reasons. These rubber bearings allow the thermal movement of the superstructures, can be easily assembled without bonding to neither superstructures nor substructures in prefabricated bridges. In most time, laminated rubber bearings are used with concrete shear keys for being not bonded to avoid the excessive displacement between superstructures and substructures.[1, 2] According to the statistics of Wenchuan Earthquake, over 80% bridges were in light damage for being simply supported on laminated rubber bearings. But with the increase of seismic intensity, laminated rubber bearings had a larger tendency to fail. Sliding of these bearings and failure of concrete shear keys were unexpectedly common in highway bridges, resulting in an excessive superstructure displacement.[3, 4] The bearing sliding can work as fuses so can protect the substructures from severe earthquake damages, which proves the good isolation performance. However, the excessive displacement between superstructures and substructures cannot be restored by laminated rubber bearings themselves. The unstable sliding with no post-yield stiffness can lead to bearing unseating or even span collapse, bringing huge difficulty in rescuing and repairing, so it is not allowed in codes.[5, 6] In China, the bearing pressure in normal service condition can be less than half of the allowance today for a conservative design, to avoid the bearing failure caused by extreme eccentric loading. Since the maximum friction force is reduced, bearing sliding is easier to happen even in the normal operation state.

Commonly used isolation rubber bearing today with unavoidable imperfections such as the temperature sensibility, high economic costs, a great effort in designing and manufacturing, heavy mass, are not suitable for the numerous medium-to-small-span bridges.[7-11] Since laminated rubber bearings are economic and widely used in many countries, it is necessary to make improvements to them. This paper aims at proposing a new type of rubber bearing, the composite rubber bearing by combining the cross sections of laminated rubber bearings and sliding rubber bearings which can be called the laminated part and sliding part respectively. For simplicity, CRB and LNB refer to the composite rubber bearing and laminated natural rubber bearing respectively below. As is shown in Fig.1, the laminated part consists of rubber layers and stiffening steel plate layers in vertical direction while the sliding part has multiple sliding layers composed of thick steel plates and Teflon plates. In normal service condition, the CRBs work as the LNBs so can satisfy the normal requirements of vertical and horizontal stiffness. In earthquakes, internal sliding occurs so lateral stiffness decreases. The seismic responses of bridges are reduced for the prolonged periods and enlarged damping.[12, 13] After earthquakes, the laminated part can provide restoring force. Compared with the LNBs, the critical displacement of the CRBs before total bearing sliding is larger so the displacement ability is improved, as shown in Fig.1. The isolation performance can be adjusted by changing the sliding area proportion and bearing pressure. Compared with popular isolation systems, CRBs have less imperfections like temperature sensibility and pollution. The CRBs are simple and cost-effective, requiring less design and manufacturing effort, so are extremely suitable for medium-to-small-span bridges.

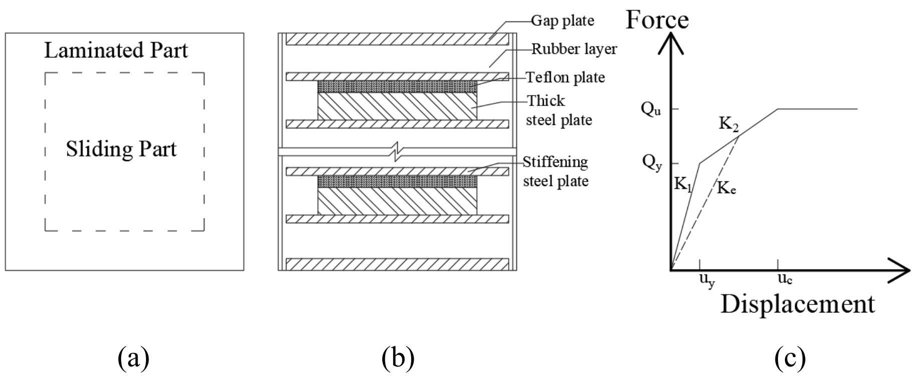


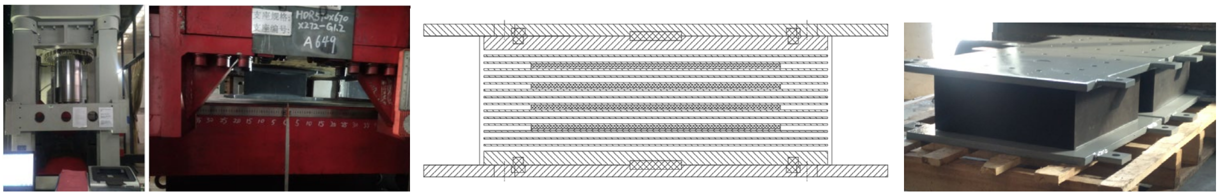
Fig. 1 – Composition of CRB: (a) plan; (b) elevation; (c) restoring-force model of CRB.

2. Experimental Testing on CRBs

To verify the mechanical properties including vertical and horizontal stiffness of CRBs, it is necessary to conduct experimental tests. Two same full-scale bearing specimens were designed and manufactured. The sizes of specimens are shown in Table 1 and the total rubber thicknesses of laminated part and sliding part were 90mm and 64mm. The testing machine, profile of bearings, specimens are shown in Fig.2.

Table 1 – Size of bearing specimens

Bearing	Total size/mm^3	Sliding area/mm^2	Fricition layers amounts
No.1	410×410×118	290×290	4
No.2	410×410×118	290×290	4



(a) (b) (c)

Fig. 2 – Experimental testing on CRBs: (a) testing machine; (b) profile of bearings; (c) full-scale specimens.

2.1 Vertical Stiffness Tests

The tests were conducted according to the test method of the specification *Lead Rubber Bearings for Highway Bridges* (JT/T822-2011)[14]. The loading pattern was four vertical loading cycles with a maximum pressure of 6MPa. No obvious damage was observed on the surfaces of both specimens after the tests. To further investigate the vertical stiffness for facilitating the design work, theoretical values of vertical stiffness were calculated according to the Chinese code *Rubber Bearings: Part 2, Seismic-Isolating Bearing* (GB20688.2-2006).[15] The vertical stiffness of the laminated part and the sliding part can be calculated respectively and the total theoretical stiffness is obtained by superposition. The results of tests and calculation are shown in Table 2. The relative errors are acceptable in engineering field. The conclusion can be drawn that theoretical formulas of the code *Rubber bearings* are still applicable to the CRB and no extra check is needed for vertical properties.

Table 2 – Vertical stiffness of CRB

Bearing No.	Test result /(kN·mm^{-1})	Theoretical stiffness/(kN·mm^{-1})	Error/%
No. 1 CRB	1294.4	1399.1	7.48
NO. 2 CRB	1236.7	1399.1	11.61

2.2 Horizontal Equivalent Stiffness Tests

According to the code *Lead Rubber Bearings for Highway Bridges (JT/T822-2011),* the horizontal equivalent stiffness and equivalent damping ratio of CRB for linear analysis can be obtained by 175%-shear-strain (157.5mm) tests. Test results are shown in the Fig.3. The average values of the results from the second to eleventh cycles were taken into consideration. The equivalent stiffness K_e and damping ratio ξ_e are compared with other isolation bearings with similar dimension and the differences are shown in the Table 3.

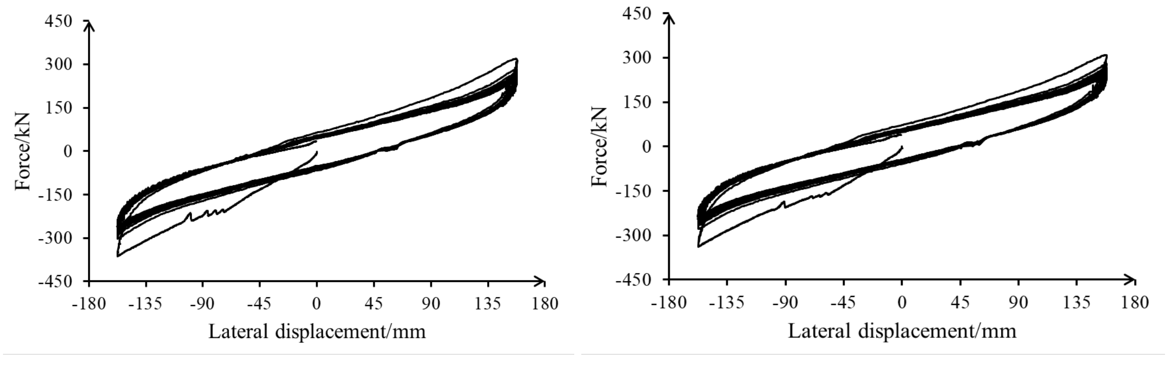


Fig. 3 – Horizontal equivalent stiffness test results: (a) No.1 CRB; (b) No.2 CRB

Among the common seismic isolation bearings, the CRBs have the least horizontal equivalent stiffness. The calculated damping ratios are underestimated for considering the strengthening parts at two ends, shown in the Fig.3. So CRBs have better isolation performance for relative high damping ratio and low equivalent lateral stiffness.

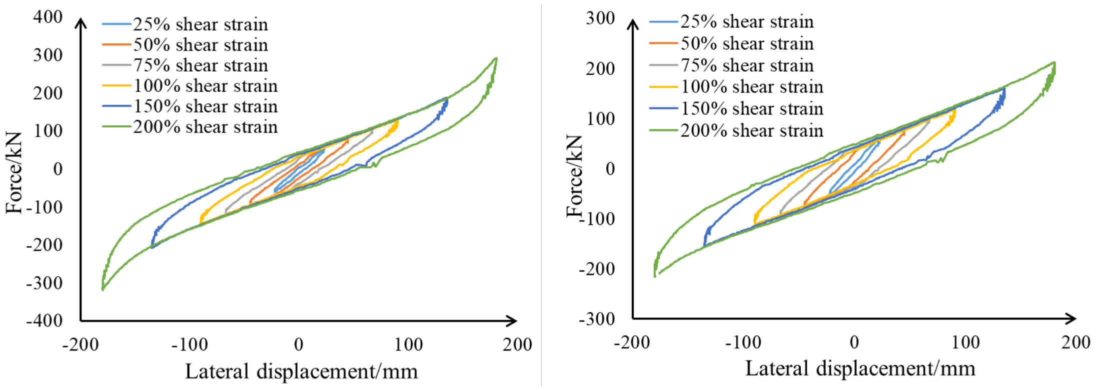
Table 3 – Comparison of seismic isolation rubber bearings

Bearing type	**Size**	**K_e / (kN·mm^{-1})**	**ξ_e (%)**
No. 1 CRB	410×410×118	1.63	10.4
No. 2 CRB	410×410×118	1.59	10.6
LRB	420×420×165	2.60	19.1
HDRB	420×420×185	1.99	15.0
LNB	400×400×99	2.25	-

2.3 Quasi-static Tests

To investigate the constitutive laws under different shear strains and the failure mode of CRBs, quasi-static tests were done. According to the Chinese code *Rubber Bearings: Part 1, Testing Methods of Seismic-Isolating Bearing (GB20688.1-2007)*,[16] the loading pattern was a three-cycle sine curve with a frequency of 0.05Hz under shear strain amplitudes of 25%, 50%, 75%, 100%, 150%, 200%. The hysteresis loops are shown in Fig.4. During the quasi-static tests, no obviously damage was seen at the bearings' surface and no sliding or failure happened.

It is demonstrated in the figure that the hysteresis curves of the CRB in small shear strains are linear, similar to LNBs. With the increase of shear deformation, the curves become bilinear and the pre-yielding and post-yielding stiffnesses of different curves are similar. When the shear strain amplitude is greater than 150%, the two ends of the curves rise upward and the stiffness strengthening occurs mainly for the hardening of rubber as mentioned above. The hardening stage is beneficial in strong earthquakes for restraining the displacement between superstructures and substructures. In design, it is conservative to neglect this stage as a safety storage.



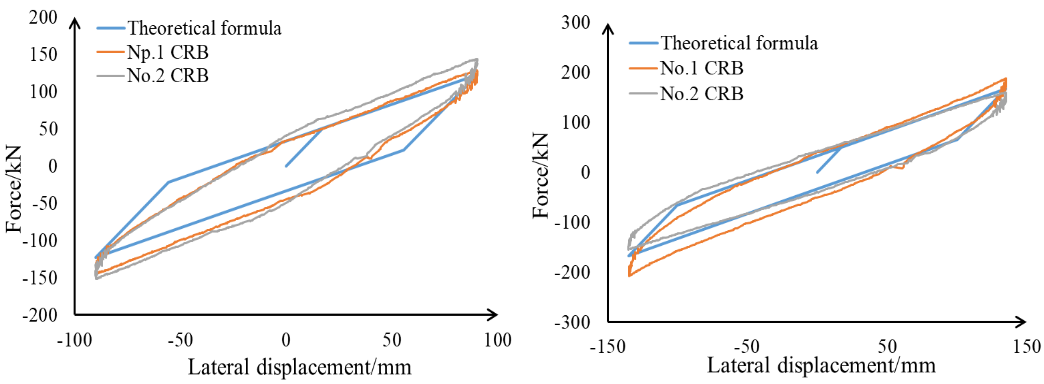
(a) (b)

Fig. 4 – Quasi-static test results: (a) No.1 CRB; (b) No.2 CRB

2.4 Derivation of Hysteretic Model

Hysteretic models can be mainly classified into two categories, equivalent linear model and bilinear model. Equivalent linear model can be used for simplifying design but the damping ratio must be modified. Even so, the equivalent linear results of capacity spectrum can be far away from true values.[17] For the accurate analysis, the bilinear model is more suitable for CRB since the post stiffening part can be ignored for conservation. The basic coefficients for a bilinear model have already been shown in Fig.1 (c), where K_1, K_2, K_e means the pre-yield stiffness, the post-yield stiffness and the equivalent horizontal stiffness. Q_y, u_y, u_c means the yielding force, yielding displacement and critical displacement before total sliding. Although these coefficients can be numerical simulated by the code formulas, it is more meaningful to derive the formulas basing on the design concept of CRB. Yielding force is dependent on the internal friction force, which can be calculated with the friction coefficient and the pressure in the sliding part. Then the friction displacement and yielding force are obtained. The pre-yield stiffness is provided by both parts while the post-yield stiffness is only provided by the laminated part. If the theoretical curve doesn't fit practical data well, adjust the pre-yield and post-yield stiffnesses by timing coefficients respectively. Finally, be aware of the critical displacement which means the bearing sliding if the bearings are not bonded.

For instance, take normal stress equals to 6MPa as in tests, the coefficients are shown in Table 4 and curves are plotted in Fig.5. The fitting effect is acceptable. It is proper and conservative to use the coefficients of 150% shear strain in larger deformation for conservation. In this case, the damping ratio of CRB can be as large as that of HDRB.



(a) (b)

Fig. 5 – Theoretical hysteresis curves: (a) shear strain of 100%; (b) shear strain of 150%

Table 4 – Theoretical coefficients of CRB hysteresis model

Shear strain	K_e/(kN·mm^{-1})	ξ_e(%)	K_1/(kN·mm^{-1})	Q_y/kN	K_2/(kN·mm^{-1})	u_y/mm	u_c/mm
100%	1.36	21.2	2.92	50.43	0.99	17.24	121.2
150%	1.24	16.8	2.92	50.43	0.99	17.24	121.2

3. Finite Element Analysis

To further investigate the isolation performance of CRB, nonlinear time history finite element analyses on medium-to-small-span bridges supported on CRBs was conducted with SAP2000, as is shown in Fig.6. The simply supported superstructures, cap beams and substructures were modeled using the beam elements, and the bearings were modeled using the link elements. For accuracy, laminated part and sliding part were modeled separately. The piles caps were modeled as lumped masses and the foundations were modeled as fixed ends. The three middle spans were taken into considerations while the other spans were treated as boundary conditions. Three artificial time histories were generated under E1, E2 earthquakes respectively by the methods introduced in Yang's literature [18]. The error of linear results between each time history and the design spectrum was no larger than 10%, to meet the need of Chinese code [19]. Only the longitudinal responses were considered and the results were compared with the LNB bridges.

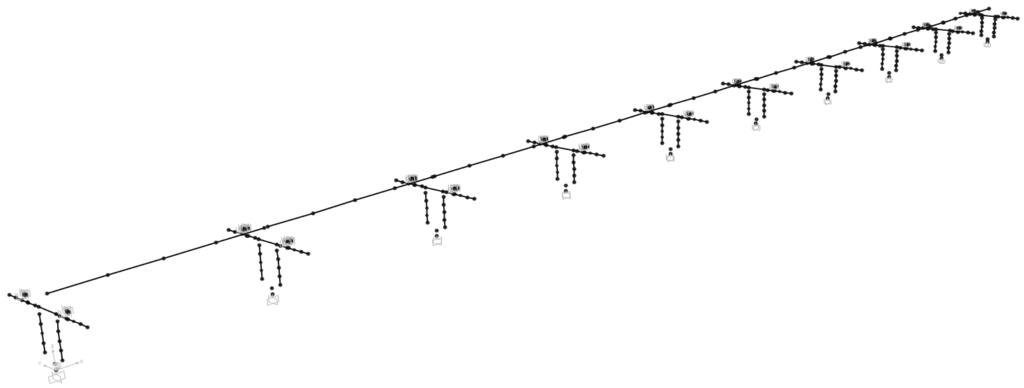


Fig. 6 – Finite element analysis on CRB bridges

Take bearing sliding into account and the coefficients of CRBs and LNBs were recalculated according to the procedures above and the pratical pressure. The critical displacement of CRBs is 84.09mm, 58.6% larger than that of LNBs. Modal analyses were done on both types of bridges and the foundation periods of longitudinal movement were 1.348 seconds for LNB bridge, 1.512 seconds for CRB bridge, proving that CRBs can prolong the natural periods.The results of the bearing displacements and shear forces are shown in Table 5, Table 6 and the bending moment of piers are shown in Table 7.

Table 5 – Responses of bearings in E1 earthquakes

E1 Earthquake	Bearing displacement/mm			Shear force/kN		
Pier No.	LNB	CRB	CRB/LNB	LNB	CRB	CRB/LNB
4	34.7	27.4	0.79	415.85	311.87	0.75
5	34.8	27.4	0.79	416.94	311.80	0.75
6	34.7	27.4	0.79	415.69	312.02	0.75
7	34.7	27.4	0.79	415.85	311.87	0.75

Table 6 – Responses of bearings in E2 earthquakes

E2 Earthquake	Bearing displacement/mm			Shear force/kN		
Pier No.	LNB	CRB	CRB/LNB	LNB	CRB	CRB/LNB
4	158.7	136.1	0.86	630.23	627.35	1.00
5	158.7	136.1	0.86	630.23	627.35	1.00
6	158.9	136.1	0.86	630.23	627.35	1.00
7	158.7	136.1	0.86	630.23	627.35	1.00

Table 7 – Bending moments at the bottom of piers

E1 Earthquake	Bending moment /(kN·m)			E2 Earthquake	Bending moment /(kN·m)		
Pier No.	LNB	CRB	CRB/LNB	Pier No.	LNB	CRB	CRB/LNB
4	6808.86	5908.02	0.87	4	14112.24	14035.84	0.99
5	6798.80	5909.48	0.87	5	14085.35	14037.98	1.00
6	6798.77	5909.48	0.87	6	14085.27	14037.98	1.00
7	6808.90	5908.02	0.87	7	14112.23	14035.84	0.99

In E1 earthquakes, the responses of CRB bridges were smaller than those of LNB bridge. The displacement storages of CRBs and LNBs before total sliding were 67.44% and 34.6%. Since both bearing types slided in E2 earthquakes, there was no difference in bending moments of piers, but the displacements of CRBs were smaller for their later total sliding. Thus, it can be concluded that the displacement ability of CRB bridges is obviously larger than that of LNB bridges, so is safer.

4. Conclusions

In this paper, composite rubber bearing (CRB) is proposed to improve the displacement ability of rubber bearings. To verify the isolation performance of CRB, experimental tests were conducted. Then hysteretic model was derived according to the design theory. Finally nonlinear time history analyses were conducted to investigate the isolation performance of CRB bridges compared with LNB bridges. The study points to the following conclusions:

1. The vertical stiffness of CRB is not weakened by the composite cross section, and the code formulas are still applicable so no extra design difficulty is caused.

2. CRB has the smallest equivalent horizontal stiffness among the seismic isolating rubber bearings with similar size. If the strengthening part of hysteresis curves in large deformation is neglected for conservation, the damping ratio of CRB can be close to that of HDRB.

3. Hysteretic model of CRB is derived and the fitting effect is acceptable. According to these formulas, the calculated critical displacement of CRB can be much larger than that of LNB so the displacement ability is greatly improved.

4. The results of nonlinear time history analyses proved the good isolation performance of CRB bridge. In small earthquakes, both displacement and force responses of CRB bridges are smaller than those of LNB bridges and the safety storage of former is much larger. In large earthquakes, the bearing sliding of CRB occurs later so the maximum displacement decreases.

Some other influential factors such as sliding part layering, self-restoring and long-term durability, local soil conditions also play an important role in the isolation performance of CRB bridges. In addition, CRB still slides in strong earthquake and restraining devices should be considered. It is necessary to take these factors into account in future studies.

5. Acknowledgements

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