

A PERFORMANCE TEST STUDY ON CHINESE G4 LEAD RUBBER BEARINGS

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SUMMARY

In this paper, the soft G4 type Chinese lead rubber bearings are studied in detail. Test contents covered fundamental properties including ultimate properties, various dependence properties and durability properties. In the fundamental property tests, results of 102 products were compiled statistically. Average values and standard deviations of the ratio between a test result and its catalog value were used as evaluating parameters. For the compressive stiffness, post-yield stiffness and yield load of the lead plug, the values of the parameters were obtained as 1.05 and 0.06, 1.04 and 0.05, 1.03 and 0.06, respectively. The products are proved to have steady quality. Tensile yielding load was confirmed to be 1.12MPa by a \$600 specimen at the shear strain of 100%. Ultimate property diagram was confirmed by several specimens. For specimens with S_2 greater than 5, $\phi 600$, $\phi 1000$ and $\phi 1100$ specimens were confirmed exceeding the shear strain of 400% under the design compressive force. Two \$\$\phi700\$ specimens and one $\phi 600$ specimen with S₂ smaller than 5, were tested until buckling occurred to confirm the validity of the proposed ultimate property diagram. The dependence tests were performed for factors such as shear strain, compressive force and temperature. For shear strain and compressive force dependence property tests, $\phi 600 \sim \phi 1100$ products were used. The durability property tests consisting of degradation and creep tests were conducted to make sure the bearing performs well after sixty years service. From the degradation test of a ϕ 300 specimen, it was found that the post yield stiffness increased by +4% and the yield load increased by +2%. The creep was estimated to be 4.4% for a ϕ 300 specimen.

INTRODUCTION

After the 1995 Hyogo-ken Nanbu earthquake in Japan and the 1999 Chi Chi earthquake in Taiwan, buildings with seismic isolation devices have increased rapidly in East-Asian area. At the same time, building codes are revised to include the design of buildings with seismic isolation devices in those countries. The building codes took effective in China and Japan in 2000 and in Taiwan in 2002. Zhou [1] had a summary on the development of China. Okamoto [2] has reported situation in Japan. On the other hand, a draft of ISO international standard was also proposed [3].

Chinese lead rubber bearings have been widely used in those areas and are expected to be used more and more. In this paper, the soft G4 type Chinese lead rubber bearings (RIL-G4) are studied in detail after

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studying G6 type lead rubber bearings [4]. The test method and evaluation method followed AIJ [5], Notification No. 1446 [6, 7] and ISO CD [3]. Test contents covered almost all aspects demanded by those building codes, such as fundamental properties including ultimate properties, various dependence properties and durability properties.

TEST MACHINE AND SPECIMENS

Test Machine

The compression-shear test machine is shown in Fig.1. The horizontal load is applied by a 2000kN dynamic servo actuator with the stroke of ± 500 mm and the vertical load is applied by a 15000kN oil jack. The test machine is designed to simulate the condition of a rubber bearing under an earthquake. The rail sliding bearings are used under the specimen to allow free horizontal deformation. Friction force aroused by the rail sliding bearings was measured using the same two sets of the bearings. Top of the specimen is restrained by the reaction beam not to rotate. Thus, the movement of the specimen in both vertical and horizontal directions is very smooth due to the horizontal rail sliding bearing and the vertical sliding device. Due to the capacity limitation of this machine, shear hysteresis tests of ϕ 1000 and ϕ 1100 specimens at the region of large deformation were performed using another test machine.





Test Specimens

Table 1 shows details of test specimens. Real size rubber bearings were used in all tests, except temperature dependence and durability property tests where ϕ 300 scale models were used. The ϕ 300 is designed to be a scale model of ϕ 600, while the ϕ 600 is designed to be a scale model of ϕ 1000. The products are designed to have total rubber thickness of 200mm. Material parameters used to calculate compressive stiffness, post-yield stiffness and yield load are summarized in Table 2.

Table 1: Details of test specimens							
311 -G4-	BII -G4	- BII -G4-	BII -G4-	BII -G4-	BII -G4		

		RIL-G4-	RIL-G4-	RIL-G4-	RIL-G4-	RIL-G4-	RIL-G4-	RIL-G4-	RIL-G4-	
		300	600M	600	700	800	900	1000-	1100	
Diameter mm		300	600	600	700	800	900	1000	1100	
Lead diameter		mm	50	80~140	80~140	90~160	100~180	120~210	130~230	170~250
Inner rubber	thickness	mm	2.5	4.0	5.0	5.0	5.0	6.0	6.0	7.0
	number		24	50	24	40	40	34	34	29
Inner steel plate		mm	2	2	2.3	2.5	2.8	2.8	3.1	4.5
Total rubber thickness		mm	60.0	200.0	120.0	200.0	200.0	204.0	204.0	203.0
1st shape factor			30.0	37.5	30.0	35.0	40.0	37.5	41.7	39.3
2nd shape factor			5.00	3.00	5.00	3.50	4.00	4.41	4.90	5.42
Critical stress N/n		N/mm ²	53	37	53	41	52	55	65	69

TEST RESULTS

Fundamental Properties

In a design practice, fundamental properties of lead rubber bearing such as compressive stiffness, postyield stiffness and yield load are needed. They can be expressed through Eq.1 and Eq.2 relating with the properties of raw materials used.

Compressive Stiffness

The compressive stiffness of lead rubber bearing can be expressed by Eq.1. The compressive stiffness of lead rubber bearing is larger than that of a pure rubber bearing without lead plug. Contribution of lead plug is included via S_1 and E_0 which is determined experimentally. Parameters relating with rubber material used in this study are summarized in Table 2.

$$K_{V} = \frac{E_{CB} \cdot A}{n \cdot t_{r}}$$
(Eq.1)
Where, $E_{CB} = \frac{E_{C} \cdot E_{B}}{E_{C} + E_{D}}, E_{C} = E_{0} (1 + 2\kappa S_{1}^{2})$

A : rubber sectional area; n : number of rubber layers; t_r : thickness of unit rubber layer

 $E_{\rm CB}$: apparent Young's modulus corrected by bulk modulus of elasticity

 E_{B} : bulk modulus of elasticity ; E_{0} : Young's modulus of rubber

 E_C : apparent Young's modulus of rubber sheet

 κ : correction factor of apparent Young's modulus according to hardness S_1 : the first shape factor

Table 2: Parameters relating with rubber material used in this study

	G (N/mm ²)	E_B (N/mm ²)	E_0 (N/mm ²)	K	α	$\sigma_{_{pb}}$ (N/mm ²)
RIL -G4	0.392	1960	1.44	0.85	0.588	8.33

Fig.2 shows typical compressive test result of a ϕ 1000 specimen. The compressive pressure was changed in the value of 10MPa±30%. Result of statistics analysis on total 102 specimens is shown in Fig.3. The average value and standard deviation is 1.06 and 0.06, respectively. In a dynamic response analysis, the compressive stiffness is usually simulated by an elastic spring.



Post-yield Stiffness and Yield Load

The post-yield stiffness and the yield load can be expressed by Eq.2.

$$K_{d} = \frac{GA}{nt_{r}} (1 + \alpha \frac{A_{p}}{A})$$

$$Q_{d} = \sigma_{pb} A_{p} \qquad (Eq.2)$$

Where, G: shear modulus; A_p : sectional area of the lead plug; α correction factor according to lead plug; σ_{pb} : yield stress of lead plug.

In Fig.4, typical hysteresis loops of three ϕ 900 specimens are compared. The compression-shear tests were conducted at the shear strain of $\pm 100\%$ under the compressive pressure of 10MPa. The specimens had three different diameters of lead plug. The diameter of lead plug was changed to 160, 170 and 180mm to investigate parameter Qd. From the test results, it can be found that the post-yield stiffness K_d was almost the same and the yield load Q_d was expressed well by the Eq.2. In Fig.5, results of statistics analysis on total 102 specimens are shown. For the post-yield stiffness and yield load, the average value and standard deviation were obtained as 1.04, 0.05 and 1.03, 0.06, respectively.



Fig.4: Typical compression-shear tests of three ϕ 900 specimens. The specimen is expressed by Type-Diameter-Lead plug-(Thickness of nit rubber layer x Number).



Tensile Yielding Load

High rise buildings with seismic isolation devices have been built more and more. In these buildings, tensile load in a bearing may occur during an earthquake. Kani *etc.* [8] and Takayama [9] have studied tension-shear characteristics based on static tests. They concluded that there is little change in properties after suffering smaller than 5% tensile strain. Feng *etc.* [10] gave the same conclusion after investigating fourteen shaking table tests where the maximum tensile stress reached 2.2MPa in lead rubber bearing. However, there is no yet any survey lasting a long enough term after suffering the tensile force. When rubber bearing suffered tensile yielding, the void will occur in the rubber layer. Thus it is important for the designer to know the tensile yielding load to determine the design criteria. A typical tension-shear stress-strain loop of a ϕ 600 specimen is shown in Fig.6. The test was performed at the offset shear strain of 100%. Followed Ohtori [11], the tensile yielding load was obtained as 1.12MPa at the tensile strain of 1%. The tensile stiffness can be estimated to be 1/5-1/10 of compressive stiffness from Fig.6.



Fig.6: A typical tension-shear strain-stress loop of a \$600 specimen. Stability and Fracture Property

Lead rubber bearings are used under various load conditions. It is important for a designer to have some criteria to judge whether the lead rubber bearings are safety enough in the assumed condition. Safety factor can be easily obtained by comparing the results of dynamic response analysis with the ultimate property diagram (UPD) as shown in Fig.7. In this study, various specimens are evaluated to confirm the proposed UPD.



Fig.7: The ultimate property diagram shown with test results of various specimens.

Critical Stress

Critical stress σ_{cr} is defined as the compress stress at zero displacement under which the rubber bearing loses its stability. It is expressed by Eq.3.

$$\sigma_{cr} = \zeta \cdot G \cdot S_1 \cdot S_2 \qquad (Eq.3)$$
Where, $\zeta = \pi \sqrt{\frac{\kappa}{8\left(1 + 2\kappa S_1^2 \frac{G}{E_B}\right)}}$

Ultimate Property Diagram (UPD)

The relationship between the compressive stress and the shear strain at ultimate state is expressed by Eq.4. The ultimate property diagram is shown in Fig.7 with test results.

$$\sigma = \sigma_{cr} \left(1 - \delta_{\max} / D \right) \tag{Eq.4}$$

Where, δ_{max} : ultimate deformation; D: diameter of rubber bearing.

According the fracture phenomenon, the ultimate property can be classified into several cases. In case I, the fracture occurs in the rubber layer at large shear deformation, which is usually observed in the specimen with larger S_2 . In case II, buckling is observed under compression-shear test of the specimen with smaller S_2 . In case III, the inner steel plate breaks under large compressive force. To verify the case I, $\phi 600$, $\phi 1000$ and $\phi 1100$ specimens were latterally deformed until the shear strain of 400% due to the limitation of the test machine. In Fig.8, test results of $\phi 1000$ and $\phi 1100$ specimens are shown. The shear force increased steadily with the increase of shear deformation. The stiffness showed hardening from about 250% shear strain in both hysteresis loops. To verify case II, $\phi 600M$ and $\phi 700$ specimens are shown. Although the applied compressive force increased two times, the shear strain at buckling decreased only about -13%. To verify case III, $\phi 600M$ was performed to over the critical stress under a pure compressive load. In Fig.7, UPD and test results are plotted. In the figure, test results of rubber bearings (RB) are also plotted for reference. It can be found that the specimens can meet the UPD well.



Fig.8: Ultimate property test results of \$1000 and \$1100 specimens.



Fig.9: Ultimate test results of \$\$\phi700 specimens under different compressive pressure.

Dependence Tests of Shear Properties

Buildings with seismic isolation devices are known to have low degree of redundancy comparing with traditional aseismic buildings. Since the performance of the buildings with seismic isolation devices are mainly determined by the characteristics of the isolation devices, mostly the shear properties, it is very important to know how the shear properties of lead rubber bearing would change when used under various conditions. Here, shear strain dependence, compressive force dependence and temperature dependence of shear properties are studied.

Shear Strain Dependence

Shear properties of lead rubber bearings change according to the shear strain. A bilinear model is known not to simulate the test result well. Feng *etc.* [12] has proposed an analytical model which is a combination of the modified bilinear and Ramberg-Osgood model (BRO). In Fig.10, hysteresis loops of ϕ 1000 specimen are shown. The post-yield stiffness was large at small shear strain and became small at large shear strain. In the hysteresis loop at the shear strain of 300%, the hardening was observed clearly. Various size specimens were also tested. Both post-yield stiffness and yield load were evaluated. The test results are summarized in Fig.11. In small shear strain, both post-yield stiffness and yield load have large values. However, comparing with the change of Kd, the change of Qd is small.

In the model proposed by Feng *etc.* [12], shear strain dependence is included by using the modified bilinear model. In the model, both post-yield stiffness and yield load could be expressed by following equations as function of the shear strain [13].

$$K_{d} = CK_{d} \cdot K_{d100}$$

$$Q_{d} = CQ_{d} \cdot Q_{d100}$$

$$CK_{d} = 0.779 \gamma^{0.43} \qquad [\gamma < 0.25] \qquad CQ_{d} = 2.036 \gamma^{0.41} \qquad [\gamma < 0.1]$$

$$CK_{d} = \gamma^{0.25} \qquad [0.25 \le \gamma < 1.0] \qquad CQ_{d} = 1.106 \gamma^{0.145} \qquad [0.1 \le \gamma < 0.5]$$

$$CK_{d} = \gamma^{0.12} \qquad [1.0 \le \gamma] \qquad CQ_{d} = 1 \qquad [0.5 \le \gamma]$$

$$CK_{d}, CQ_{d}$$
: shear strain dependent coefficients

 $\bar{\gamma}$: shear strain

Where

 K_{d100} : post-yield stiffness at shear strain 100%

 Q_{d100} : yield load at shear strain 100%



compression-shear test shown in Fig.10.

If lead rubber bearings are used together with other isolation devices such as sliding bearing, estimation of the vertical deformation at a shear strain is also very important. Different vertical deformation among the devices will lead additional stress on other structural elements such as beams. The vertical deformation vs.

the horizontal deformation of the specimen shown in Fig.10 is shown in Fig.12. At the shear strain of 200%, the vertical deformation was only 2mm. However when the shear strain increased to 300% and 400%, the vertical deformation increased rapidly to 7mm and 22mm, respectively. In other words, the compressive stiffness decreases with the increase of shear deformation, especially at the region of large shear strain.

Compressive Force Dependence

The shear stiffness of lead rubber bearings becomes smaller when the compressive force increases. Fig.13 shows typical hysteresis loops under different compressive force conditions. The specimen was ϕ 600 specimen which is designed to be used under the compressive stress of 15MPa. To investigate the compressive force dependence, the compressive stress was changed from 7.5, 15 and 22.5 to 30MPa at the shear strain of 100%. Even under two times of the design load, the hysteresis loop showed very steadily. The same test was carried out on various size specimens whose results are summarized in Fig.14. Comparing the change of Kd, the change of Qd is small.

It is difficult to consider the compressive force dependence in the dynamic response analysis. Kato *etc.*[14] proposed a new approach to this problem. In their conclusions, the dynamic response results of the shear deformation differed little under a moderate change of compressive force. But the vertical deformation as shown in Fig.12 can be simulated well.



Fig.13: Hysteresis loops of the specimen ϕ 600 under different compressive stress conditions. Friction force was not corrected in the figure.



Fig.14: Compressive force dependence of shear properties evaluated for various specimens.

Temperature Dependence

Lead rubber bearings are used in various places. The temperature dependence of shear properties shall be considered in the design practice. The rubber material and lead plug usually become harder at low temperature and softer at high temperature. The structural designer should design the building according to the temperature change of the building site. Temperature dependence of shear properties was studied using a \$300 scale model. The test specimen was put into the thermostatic oven to be maintained at the specified temperature conditions. A routine test of 100% shear strain was conducted after taking it out as quickly as possible. The post-yield stiffness and yield load were evaluated. The test results are shown in Fig.15. Comparing the result at 20°C, the post-yield stiffness changed about +5% at -10°C and only -2% at +40 °C. On the other hand, the yield load changed +25% at -10°C and -13% at +40 °C. The equation proposed in reference [15] shown in Eq.6 could be used.

Where, t_0 : target temperature, t: reference temperature (=20 °C)



Durability Tests

Since a building is usually designed to be used for over 60 years, rubber bearings should have also enough safety. Accelerated ageing test is widely used to understand the vulcanized rubber's characteristics such as tensile strength, elongation caused by heating within a short time. The tests were planned based on Arrhenius Theory. From the results of the raw inner rubber material test, it was found that the condition at a temperature of 100°C for 10 days corresponded using condition at a temperature of 20°C for 60 years for rubber bearings. All durability tests followed this condition.

Degradation Test

Rubber material is known to have chemical reaction with oxygen, ozone and ultraviolet ray in the air. The material usually becomes harder so that the stiffness of a rubber bearing will become larger too. To the contrary, lead plug is known to change little inside the hole. Changes in characteristics of rubber bearings after 60 years should be considered in the response analysis of the building. Miyazaki *etc.*[16] investigated several lead rubber bearings used for ten years and concluded that the post-yield stiffness increased less than +8% and the yield load changed little. In this study, a ϕ 300 specimen was aged in a heating oven with the temperature of 100°C for 10 days followed Arrhenius Theory. Then the specimen was cooled off for 24 hours naturally, to keep the temperature in the whole specimen uniform. A routine test of 100% shear strain was conducted. The test results are shown in Fig.16. From hysteresis loops, it was found that the post-yield stiffness increased by +4% and the yield load increased by +2% after 60 years service.



Creep Test

An estimation of axial shrink of rubber bearings under design load is important since different shrinks will lead additional stress on other structural elements. This phenomenon will occur especially in case of different devices such as rubber bearings and sliding bearings are used together. In a survey conducted by Miyazaki *etc.*[16], the creep was found to be 1mm (0.4%) after used for ten years. From that result, the creep after used for sixty years may be estimated as 3.6mm (1.5%). In this study, creep strain was estimated by a accelerated aging test at high temperature condition. A ϕ 300 specimen was heated at 100°C for 10 days followed Arrhenius Theory. The result is shown in Fig.17. The creep strain was estimated to be 4.4%.



Fig.17: Creep test result at high temperature of a ϕ 300 specimen.

CONCLUSIONS

The soft G4 type Chinese lead rubber bearings are studied in detail. Test contents covered fundamental properties including ultimate properties, various dependence properties and durability properties. Conclusions could be remarked as follows:

- I. From the results of the statistical analysis on total 102 specimens, the characteristics of lead rubber bearings was found steady enough.
- II. The proposed ultimate property diagram was verified by tests of several specimens including $\phi 1000$ and $\phi 1100$ specimens deformed to 400% shear strain.
- III. Various dependence tests on shear properties were conducted. All the test results were compiled well to use.

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