Product Specification and Mechanical Properties of Chinese Rubber Bearings

Wenguang Liu[1)], Fulin Zhou[1)], Feng Sun[1)], Da Huo[2)], Weiming Yan[2)]

1) Guangzhou University, 510405,Guangzhou, P R China
2) Beijing Polytechnic University, 100022, Beijing, P R China

ABSTRACT

Firstly, the basic mechanical properties of rubber bearings are provided in the paper, such as the vertical stiffness, and horizontal stiffness of the rubber bearings with diameter from 400mm to 1000mm. Then the duration properties of acceleration aging, creep test are considered followed by the product specification. The dependence properties, vertical compressive stress 5MPa to 25MPa, frequency 0.001Hz to 0.5Hz, temperature -25ºC to 40ºC, are also introduced in the paper. According to the product specification, rubber bearings should have enough fireproof capability under the action of natural fire lasting one hour, the fireproof properties of rubber bearings and lead rubber bearings was tested. The mechanical properties of rubber bearings with rotation are also provided in the paper, they show that Chinese rubber bearings have stable properties not only can be used in base isolation system but also in column top isolation system. At the end of the paper, the main features of product specification of laminated rubber bearings are introduced.

INTRODUCTION

Base isolation system shows an effective avenue to aseismic design, there are nearly 250 isolated buildings in China since the first one was built in 1994. The isolated buildings are distributed widely according to the statistics provided by Chinese Committee of Seismic Control for Structures (CSACE), especially in Xinjian, Shanxi and Yunnan province. The usage of base isolation system has been extended from special purposes such as computer centers or hospital to normal residential buildings, and the structural types include reinforcement concrete and masonry. In the mean time, rubber bearings have been used in railway and highway bridge to decrease the response under the action of earthquake. Being an important part of the structure, the properties of rubber bearings are the key factors to support the vertical load and provide enough displacement, or provide enough damping for lead rubber bearings.

In 1997, China began to compile product specification of laminated rubber bearings in order to promote the development of isolated building, and the specification is published in October of 2000. In this paper, the properties of rubber bearings and test results that we completed in China and Japan are summarized and compared, and then the product specification are introduced in the end of the paper.

MECHANICAL PROPERTIES OF RUBBER BEARINGS

Vertical Stiffness and Yield Stiffness

The vertical stiffness and yield stiffness of specimens with diameter from 400mm to 1000mm are tested, the properties of natural rubber used in the specimens are as follows: Gr=0.55MPa; Eb=2kN/mm^2; κ=0.77; IRHD (hardness)=48. The comparison between design value and test value of vertical stiffness are provided in figure 1, which includes 10-ϕ400 to 10-ϕ1000 specimens. The equations of vertical stiffness and yield stiffness are:

$$K_v = \alpha \frac{E_{cb} G_r}{A} \tag{1}$$

$$K_d = \frac{K_{eq}\delta - Q_d}{\delta} \tag{2}$$

Extreme Properties

The monotonic shear failure tests with vertical compressive stress 10MPa were performed using 4 different diameter LRB specimens and 2 different diameter RB specimens. The hysteresis loops of LRB specimens are shown in

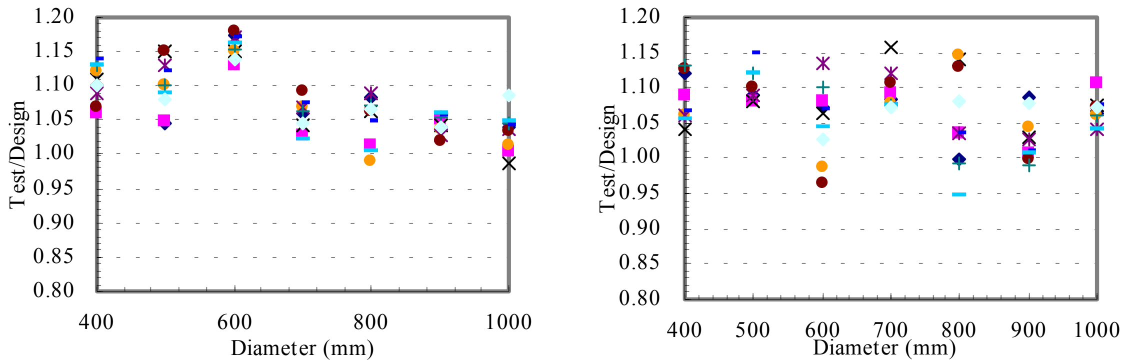

Fig. 1 Vertical stiffness and yield stiffness (test value/design value, design compressive stress 10MPa)

figure 2. The extreme shear strain of all specimens are more than 350% which is the minimum extreme strain published by the product standard, and the largest shear strain is 478%.

Creep and Aging Test

The tests were planned based on the Arrhenius's Theory. From the results of the raw rubber material test, it was found that the condition 100°C × 168 hours corresponded the condition 20°C×60 years for rubber bearings. All durability tests followed this condition. A RB-ϕ300 and LRB-ϕ300 specimen was used to perform creep test to keep vertical load small enough. The result is shown in figure 3. The vertical displacement does not include elastic deformation of the specimen. The creep is small as much as 1.38 mm and 0.91 mm or 2.38% and 1.58% by strain respectively.

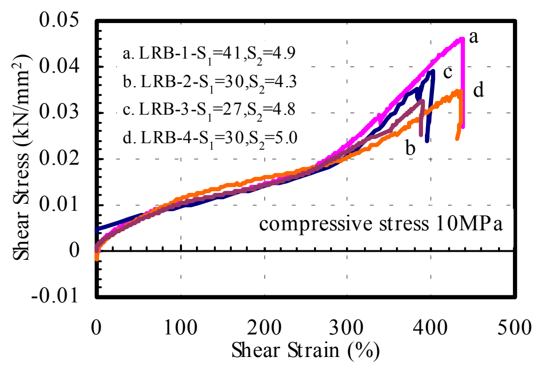

Fig. 2 Extreme shear strain

Four specimens, RB-ϕ300, RB-ϕ400, LRB-ϕ300 and LRB-ϕ200 are used for the acceleration aging test in the terms of corresponded condition 20°C×60 years respectively. The horizontal and vertical stiffness of both RB and LRB specimens increase nearly 10% when specimens cooled more than 24 hours after the aging test. The extreme shear strain of aging specimens are tested to compare with the original specimens under the same test condition, and the LRB-ϕ300 specimen are not failure when the shear strain is more than 360% for the reason to protect the test facilities, see in figure 4.

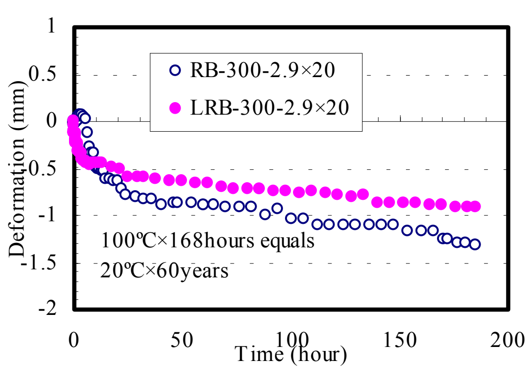

Fig. 3 Creep of RB-300 and LRB-300 with constant compressive stress 10Mpa

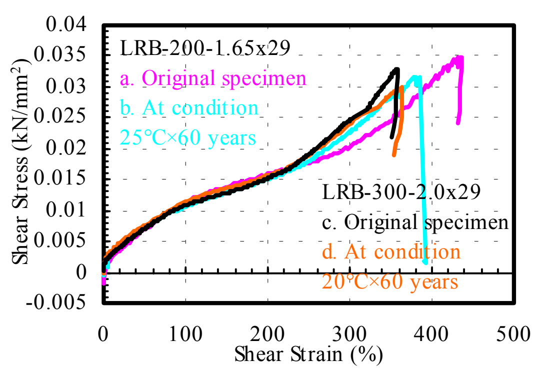

Fig. 4 Extreme shear strain of aging test

Fireproof Test

2 specimens are used for the fireproof test according to the demand of specification. The test is to imitate the engineering condition of rubber bearings, adding stable vertical load to design value and using wood with a little patrolling around the specimen, keeping the fire lasting for one hour. There are 2 temperature transducers to collect the variation of inner and outer temperature of the specimens, see in figure 5. The outer average temperature of the specimen is 350°C, the temperature of the inner specimen increases about 15% in the first 20 minutes, and then the temperature of the inner increases apparently. The vertical stiffness decrease nearly 7% and the horizontal stiffness decrease nearly 8% compared to the original specimen. The extreme compressive property has no apparent difference for both 2 types specimen when the stress is no more than 70Mpa, the extreme compressive stress is more than 90MPa determined by the specification from the figure 6. The inner rubber is nature rubber and the outer is neoprene rubber, it is observed that nearly 3mm thick carbonization is formed on protection rubber surface after the fireproof test.

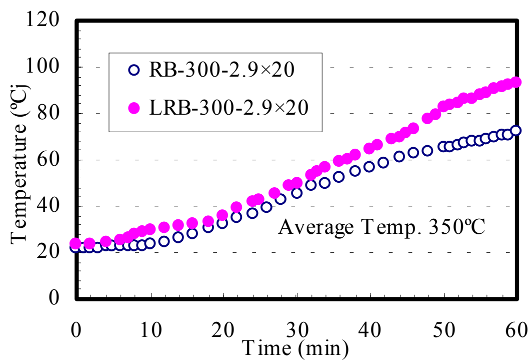

Fig. 5 Temperature of inner rubber

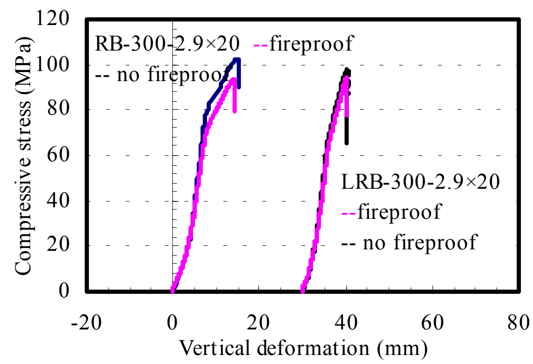

Fig. 6 Extreme compressive stress after fireproof test

Dependence

Dependence properties, such as compressive stress, shear strain, frequency, fatigue and temperature dependence, are also tested to grasp the characteristics of rubber bearings. The mechanical properties of stiffness and damping of rubber bearings should have little decline or increase. The environment temperature of rubber bearings varies according the climate. The vertical load to the rubber bearing changes greatly under a moderate to large earthquake. It is important that the building has enough safety under all these handicaps. The compressive stress from 5Mpa to 25MPa, temperature –25to 40ºC and load frequency 0.001Hz to 0.5Hz dependence of LRB-ϕ300 are shown in one figure with different horizontal axis, and another axis is a relative ratio normalized with the stiffness of 100% shear strain, see in figure 7.

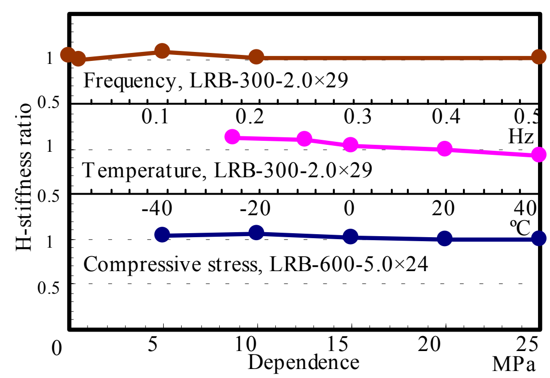

Fig 7. Dependence Properties (Compressive stress 5-25MPa, Temperature -25-40ºC, Frequency 0.001-0.5Hz)

Rotation

The mechanical characteristics take vertical stiffness, horizontal stiffness and yield stiffness for example, will vary when the test specimens create shear strain with fixed or unfixed rotation. 5 cases with different compressive stress, rotation and shear strain are considered to compare with a traditional test without rotation, the test contents are shown in table 1. The specimens used in the test are RB-ϕ300 and LRB-ϕ300.

The test results of both RB and LRB specimens are close in case 1,2 and 3, which have fixed rotation according to the shear strain-horizontal stiffness relationship shown in Figure 8. On the other hand, the load-displacement curve turns low when rotation of specimens vary in the test process in case 4 and 5.

Table 1. Test Contents with Rotation

Case	Compressive stress (MPa)	Rotation (rad.)	Shear strain (%)
1	10	0.0	10%~300%
2	5~15	0.0	10%~300%
3	10	+0.01	10%~300%
4	10	-0.01~+0.01	10%~300%
5	5~15	-0.01~+0.01	10%~300%

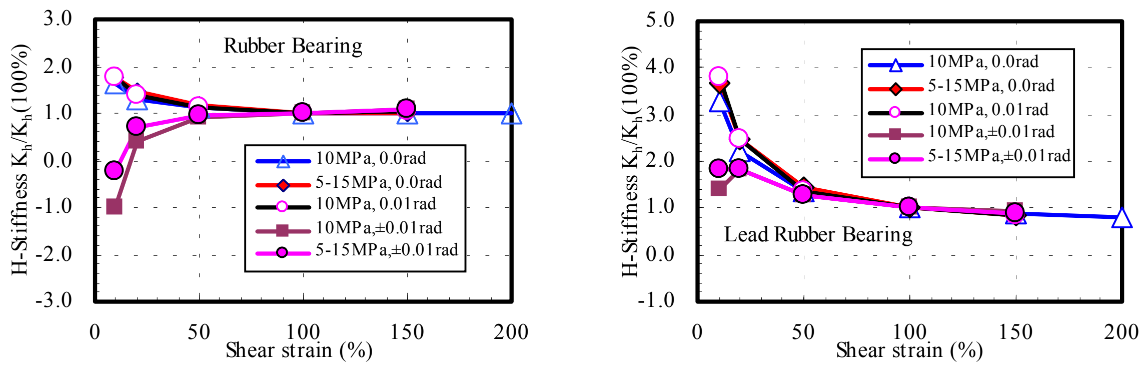

Fig. 8 Comparison of horizontal stiffness (Left: RB, Right: LRB)

The stiffness of RB turns stable with the increase of shear strain indicated in Figure 8, which is normalized with the value at shear deformation γ=100% in 5 cases. The test results of LRB are shown in Figure 8 too, it shows that mechanical characteristics are not stable in small shear deformation, however, the curve turns more stable when shear strain is more than 50%. The horizontal stiffness of RB specimen and yield stiffness of LRB specimen at shear strain γ=100% are shown in Table 2, which are normalized with the values tested in case 1.

Table 2. Horizontal stiffness and yield stiffness (Normalized with the value tested in case 1)

Specimen	Case 1	Case 2	Case 3	Case 4	Case 5	Case 1/numerical value
RB	1	0.913	0.903	0.699	0.728	0.985
LRB	1	1.001	0.904	0.746	0.811	0.982

PRODUCT SPECIFICATION

Properties of Rubber Bearings

Vertical and horizontal mechanical properties are shown in table 3.

Table 3. Vertical and horizontal mechanical properties

Item		Properties
Vertical properties	Stiffness	±20% of design value, ±10% of average value
	Deformation	$\left\lvert\frac{K_v(1,2,4,5)-K_v(3)}{K_v(3)}\right\rvert \le 10\%$ K_v(i): stiffness of i cycle
	Extreme compressive stress	≥90Mpa
	Elastic compressive stress	≥70Mpa
	Extreme compressive stress with horizontal displacement 0.55 rubber diameter	≥30Mpa
	Extreme tensile stress	≥1.5Mpa
	Elastic tensile stress	≥1.0Mpa

Horizontal properties	Stiffness	±20% of design, ±10% of average value (For inspection, shear strain 50,100,250% should be tested)
	Yield stiffness	
	Effective damping ratio	
	Extreme strain	≥350%

Durability properties, such as aging, creep, fatigue properties are shown in table 4.

Table 4. Durability properties

Item		Properties
Aging	Vertical stiffness	Varying percentage less than 20%
	Horizontal stiffness	
	Horizontal extreme strain	
	Effective damping ratio	
Creep	Deformation of rubber	Less than 5% of total thickness of rubber
Fatigue	Vertical stiffness	Varying percentage less than 20%
	Horizontal stiffness	
	Effective damping ratio	

Varying percentage of vertical stiffness, horizontal stiffness and effective damping ratio is less than 30% after the fireproof test. Dependence of rubber isolator should consider the vertical compressive stress, large shear strain, loading frequency and temperature.

Horizontal Conversion Intensity

A new concept, horizontal conversion intensity, is provided for analyzing the structural earthquake response instead of protected intensity used in calculating the earthquake response in China aseismic design code for traditional building. The horizontal conversion intensity is defined as follows:

(1) The intensity value is determined through the comparison of layer shear force between isolated building and non-isolated building. The horizontal conversion intensity equals to the protected intensity which is lowed, when isolated structure layer shear force less than 80% layer shear force of non-isolated structure with protected intensity lowed.

(2) For masonry structure and structures with basic period no more than site characteristic period, horizontal conversion intensity can be derived as follows:

The basic period of isolated structure is no less than the first critic period and the ratio to site period is no less than the minimum ratio that is shown in table 3, the horizontal conversion intensity is 1 degree lower than the protected intensity of site.

The basic period of isolated structure is no less than the second critic period and the ratio to site period is no less than the maximum ratio that is shown in table 5, the horizontal conversion intensity is 2 degree lower than the protected intensity of site.

(3) Horizontal conversion intensity should not be 2 degree lower than the protected intensity, and it should not be lower than 6 degree.

Table 5. Critic period and ratio of site characteristic period

Effective damping ratio	First critic period	Minimum ratio	Second critic period	Maximum ratio
0.05	1.1s	2.8	2.4s	6.0
0.10	0.85s	2.1	1.9s	4.8
0.15	0.72s	1.8	1.6s	4.1

Computation of Earthquake Response

The methods to calculate the earthquake response of isolated structure have effective lateral method and time-history method of earthquake response analysis.

The earthquake affective coefficient α_{max} with the damping ratio 0.05 can be adopted by protected intensity, site type and free vibration period of structure, which is shown in figure 1. Shape coefficient of the curve is constituted as follows:

(1) Linear ascending part, the period is less than 0.5s.
(2) Level part, 0.1s to characteristic period T_g.
(3) Descent part, T_g to 5 T_g, and the attenuation coefficient are 0.9.
(4) Slant part, 5 T_g to 6s, descent slope is 0.02.
(5) Characteristic period T_g, determined by the site and earthquake environment: 1st distinct shown in table 6, 2nd distinct $T_{g2} = \frac{7}{6} T_g$, 3rd distinct $T_{g3} = \frac{4}{3} T_g$.

Table 6. Characteristic period T_g of 1st distinct

Site	I	II	III	IV
T_g (s)	0.20	0.30	0.40	0.65

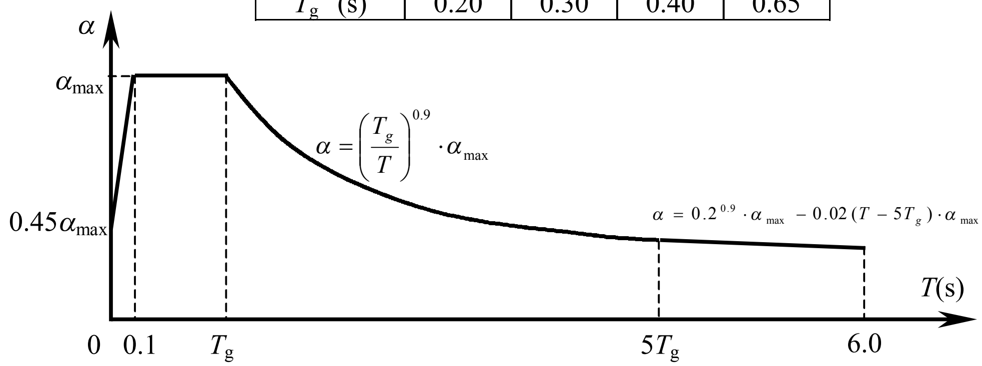

Fig. 9 Earthquake affective coefficient curve

When damping ratio of structure is not 0.05, the lateral earthquake affective coefficient curve is same as figure 1, but the shape coefficient should be corrected as follows:

(1) The attenuation coefficient γ of descent part is:

$$\gamma = 0.9 + \frac{0.05 - \zeta}{0.5 + 4\zeta} \tag{3}$$

(2) Slope η_2 of slant part is:

$$\eta_2 = 0.02 + \frac{0.05 - \zeta}{8} \tag{4}$$

The maximum affecting coefficient of lateral earthquake α_{max} should be adopted as follows:
(1) When structural damping is 0.05, α_{max} is shown in table 7.

Table 7. The maximum affecting coefficient of lateral earthquake α_{max}

Intensity	6	7	8	9
Little Earthquake	0.04	0.08	0.16	0.32
Middle Earthquake	0.113	0.23	0.45	0.90
Large Earthquake	0.25	0.50	0.90	1.40

(2) When structural damping ratio is not 0.05, α_{max} should consider of the correction coefficient η_1:

$$\eta_1 = 1 + \frac{0.05 - \zeta}{0.06 + 1.4\zeta} \tag{5}$$

The standard value and distribution of earthquake action should be considered as follows:
(1) The equations of standard value of total lateral earthquake action are:

$$F_{ek} = \alpha_1 G \tag{6}$$

$$\zeta = \frac{\sum K_i \zeta_i}{\sum K_i} \tag{7}$$

(2) For masonry structure and structures with height-width ratio less than 2, the lateral earthquake action of mass point is:

$$F_i = \frac{G_i}{\sum G_i} F_{ek} \tag{8}$$

(3) For other structures, the lateral earthquake action of mass point is:

$$F_i = \frac{G_i H_i}{\sum G_i H_i} F_{ek} \tag{9}$$

The equation to calculate the lateral displacement of isolation layer with effective lateral method is:

$$U_h = k \frac{F_{ek}}{\sum K_i} \tag{10}$$

The lateral displacement of isolator or damper should corrected with displacement coefficient η_t when torsion is considered, and η_t is:

$$\eta_t = 1 + 12\, e\, r / (b^2 + l^2) \tag{11}$$

The choice of earthquake input wave, computation model and torsion action of 2-direction lateral earthquake action should be considered with time history method of earthquake response analysis to calculate structural response for isolated building.

CONCLUSION

The basic mechanical properties of Chinese rubber bearings are stable according to the statistics provided in the paper, the duration properties of acceleration aging, creep test show that Chinese rubber bearings have enough safety after 60 years followed by the product specification. The further, the dependence properties, such as different compressive stress, frequency, shear strain, temperature dependence, testify that all specimens have stable properties even if work in different conditions. The vertical stiffness and horizontal stiffness tested after the fireproof test decrease no more than 8% and the extreme compressive stresses are still more than 90MPa. The mechanical properties of rubber bearings with rotation are also provided in the paper, they show that Chinese rubber bearings have stable properties not only can be used in base isolation system but also in column top isolation system. A new concept, lateral conversion intensity is provided for design and analyzing the isolated structure in specification. Structural elements above isolation layer can be designed with lateral conversion intensity that is lower than protected intensity, reducing the cost of isolated building while structural safety is ensured.

NOMENCLATURE

K_v = vertical stiffness
α = coefficient
G_r = shear modulus
A = area of section
K_d = yield stiffness
K_{eq} = equivalent stiffness
δ = shear deformation
Q_d = yield load
ζ = damping ratio
F_{ek} = standard value of total lateral earthquake action of structure
α_1 = affecting coefficient of lateral earthquake action corresponded to free vibration period of isolated structure

G = total gravity value of structural elements above isolation layer
ζ = effective damping ratio of isolation layer
K_i = effective stiffness of single isolator
ζ_i = effective damping ratio of single isolator
U_h = displacement of isolation layer.
k = near site coefficient, the distance to causative fault $d \le 5$km, $k=1.5$; $5km < d \le 10km$, $k=1.25$; $d > 10km$, $k=1.0$.
r = distance between isolator and rigidity center of isolation layer
b, l = short, long side of structural plane.
e = eccentricity between mass center of structure and rigidity center of isolation layer, which include actual eccentricity and occasional eccentricity (0.05b)

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