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A DETAILED EXPERIMENTAL STUDY ON CHINESE LEAD RUBBER BEARING

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SUMMARY

Characteristics of Chinese lead rubber bearing were tested. Vertical stiffness test, compression failure test and tensile failure test are studied first. Standard cyclic shear tests are performed for a shear strain range of 10%~200%, with axial stress varying from 5MPa to 15MPa. The test specimens begin from ϕ200, ϕ400 to the real size of ϕ800 and ϕ1000. In vertical compression failure test of a ϕ200 specimen, it was found that the specimen could stay elastic until stress σ_{ec}=900kgf/cm^2, and corrupted at a stress of σ_{uc}=1260gkf/cm^2. In the tensile failure test, the specimen was found to stay elastic until σ_{et}=19kgf/cm^2 and corrupt at tensile stress of σ_{ut}=35kgf/cm^2. Several kinds of shear test were performed used ϕ400 and ϕ200 specimens. A ϕ200 specimen was tested up to shear strain of 435% without visible damage. Fatigue test of a ϕ400 specimen was dynamically tested at shear strains of 50% and 100% for a total of 200 cycles. Compared with the value of 3rd cycle, the stiffness of 50th cycle decreased by -15% while damping factor decreased by -10%. In the temperature dependence test, the stiffness increased by +13% at -20^{o}C compared with that at 20^{o}C. The Durability test was performed to understand the characteristics of lead rubber bearings after 60 years service. The creep was found to be 0.22mm or 0.22/48=0.5% by strain for a ϕ200 specimen. From the accelerated ageing test of a ϕ400 specimen, it was found that the vertical stiffness increased by +7%, the post-yield stiffness increased by +6%.

INTRODUCTION

The concept of base isolation is gaining widespread acceptance not only in engineering community but also in the general public society. The increasing number of base-isolated buildings in Japan is a good parameter to show this. There were about only 80 base-isolated buildings before 1994. After the 1995 Hyogoken-Nanbu earthquake, the number of base-isolated buildings increased to about 630 at the end of February 1999. Three types usage has been widely used, which are natural rubber bearings with extra dampers, high damping rubber bearings and lead rubber bearings. A lead rubber bearing provides an economic solution in that the one unit incorporates the three functions of vertical support, horizontal flexibility and hysteresis damper. Skinner R.I. etc (1993), Zhou, F.(1997) have very good summaries on them. Usually, the cost of a base-isolated building is higher by 3%~10% than that of a conventional aseismic one in Japan. To keep the cost of a base-isolated building equal or even cheaper, lead rubber bearings, which are low cost and have good quality, are demanded by the market.

Shantou Vibro Tech Industrial and Development Co. Ltd. (VIBRO), China has started to produce rubber bearings from 1992 with helps from UNIDO(the United Nations Industrial Development Organization). In this paper, characteristics of Chinese lead rubber bearings are tested. Specimens are designed to satisfy the usage in

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Japan. The test content followed the draft standard from Japan Society of Seismic Isolation (1996). It includes all aspects needed by the designer such as dynamic hysteresis property and durability property.
Vertical stiffness test, compression failure test and tensile failure test are studied first. Standard cyclic shear tests are performed for a shear strain range of 10%~200%, with axial stress varying from 5MPa to 15MPa. In the building plan, rubber bearings are usually designed to have an average stress of 10MPa and shear strain of 150% under a level II earthquake proposed by Building Center of Japan (BCJ). For the response analysis various dependence characteristics such as shear strain dependence, vertical load dependence, fatigue test, frequency dependence and temperature dependence are analyzed. Durability tests were performed to understand the characteristics of lead rubber bearings after 60 years service. Shear failure test after 60 years is performed to compare with the original one.

2. TEST FACILITIES AND TEST SPECIMENS

2.1 Test Machine and Measurement

The shear test machine is shown in Fig.1 and Photo 1. The horizontal load was applied by a dynamic actuator and the vertical load was applied by a static jack. Details around the specimen are also shown in Fig.3. The test machine was designed to simulate the condition of a rubber bearing under an earthquake. The roller bearings were used to allow free horizontal deformation. Top of the specimen was restrained by the reaction frame not to rotate. On the other hand, the movement of the specimen in the vertical and horizontal direction was very smooth due to the horizontal bearing and the vertical slide device.
Several displacements were measured in the locations shown in Fig.3. There were 2 horizontal and 4 vertical displacement transducers. The horizontal displacement transducers were placed in the actuator direction. The vertical transducers were placed in corners. Load and displacement data was recorded in a personal computer.
Part of shear hysteresis tests was also performed using the double specimen test machine shown in Fig.2. For the real size rubber bearing test, a test machine same with the one shown in Fig.1 was built which have a 200tf horizontal actuator of ±500mm stroke and 1500tf vertical actuator.

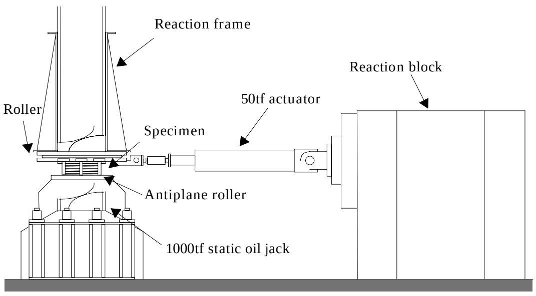

Fig.1: The single specimen test machine

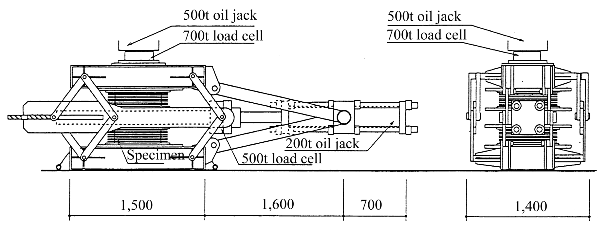

Fig.2: The double specimens test machine

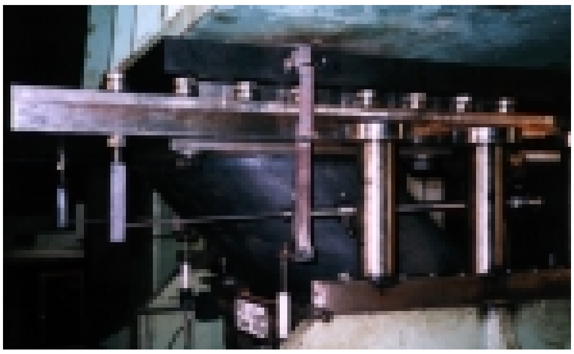

Photo.1: Photo of the test machine

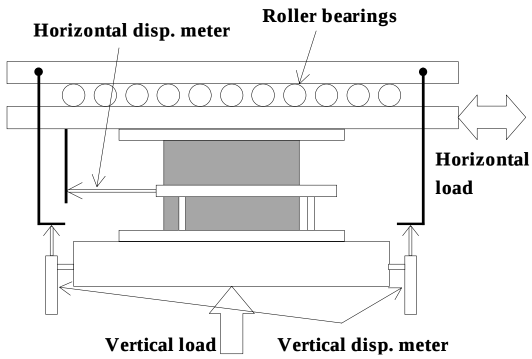

Fig.3: Displacement transducers

2.2 Test Specimens

5-ϕ400 type and 3-ϕ200 type lead rubber bearings were used in tests. The details are shown in Table 1. ϕ400 type is 2/3 and ϕ200 is 1/3 scaled model corresponding to the full scale ϕ600 type. The specimens were designed to have 1st shape coefficient (S_1) being around 30 and 2nd shape coefficient (S_2) being 4. These values of the shape coefficients are popular in Japan. The real size ϕ800,ϕ1000 type lead rubber bearings are shown in Table 1 also.

Properties of natural rubber used in the specimens are as follows: G=0.55MPa; Eb=2kN/mm^2; κ=0.77; IRHD(hardness)=48.

Table 1 Details of rubber bearings

	φ200	φ400	φ800	φ1000
Diameter*height (*mm*)	195*130	400*183	800*393.2	1000*392.3
inner steel plate	28@1.5mm	28@2mm	40@5mm	34@6mm
inner rubber plate	29@1.65mm	29@3mm	39@2.8mm	33@3.1mm
diameter of lead (*mm*)	40	80	160	220
1st shape coefficient	29.5	33.3	40.0	41.0
2nd shape coefficient	4.08	4.60	4.0	4.9

3. TEST RESULTS

3.1 Vertical Tests

The vertical stiffness test and the vertical tensile failure test were carried out at a 100tf amsler type universal testing machine shown in Photo 2. The compression failure test was performed at the shear test machine shown in Fig.1.

3.1.1 Vertical stiffness

A φ400 specimen was used to perform vertical stiffness test. 10MPa±30% of vertical design stress was statically applied to the specimen. Vertical load and displacement relation is shown in Fig.4. The 3rd cycle of a total 5 cycles (7MPa~13MPa) was used to calculate vertical stiffness. The stiffness was 1794kN/mm, the displacement corresponding to the design load was 1.2mm. The natural frequency under the design load is 19Hz.

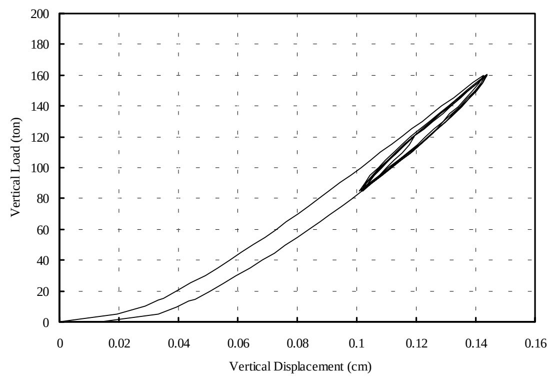

Fig.4: Vertical load and displacement relation

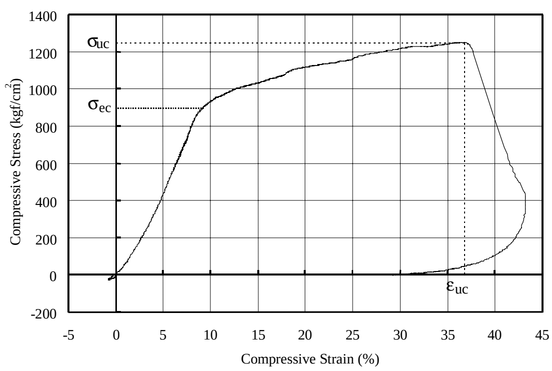

Fig.5: Compression stress and strain relation of a φ200 specimen.

3.1.2 Compression failure test

Usually, the extreme load of a rubber bearing is decided by the accuracy to place the inner steel plate in parallel and bonding strength between the steel plate and the rubber plate when manufacturing.

Compression failure test was performed using a φ200 specimen. Compression stress-strain relationship is shown in Fig.5. It was found that the specimen could stay elastic until stress of σ_{ec}=90MPa, and corrupted at stress of σ_{uc}=126MPa with strain of 37%. After the specimen bulked at the load σ_{ec}, the stiffness decreased extremely and the specimen corrupted at the load σ_{uc}.

3.1.3 Tensile failure test

A φ200 specimen was used to perform tensile failure test. The tensile test machine is shown in Photo 2. Two vertical displacements and applied load were measured.

Tensile stress-strain relationship is shown in Fig.6. A drop of stress at the tensile strain 180% was caused by the hold of tensile load. The specimen stayed elastic until stress of σ_{et}=1.9MPa and corrupted at tensile stress of σ_{ut}=3.5MPa with strain of 295% which means 3 times of the total thickness of rubber plates. The stiffness of the specimen decreased extremely after the load σ_{et}. The tensile displacement was very large as much as 140mm at the tensile failures.

Photo 2: Photo of the tensile test machine

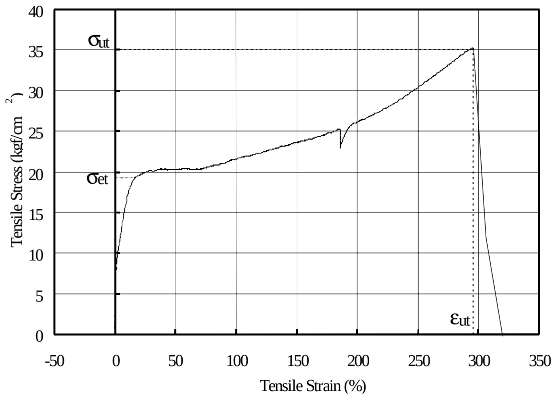

Fig.6: Tensile stress and strain relation of a φ200 specimen.

3.2 Shear Tests

3.2.1 Damping factor and stiffness

A φ400 specimen was used to perform standard cyclic shear tests with a shear strain range of 10%~200%, with axial stresses of 5, 10, 15MPa. Typical hysterisis loop of horizontal load-displacement relationship compared with the design model is shown in Fig.7. It is the 3rd cycle in total 5 cycles of the test with shear strain of 100% under axial stress of 10MPa.

For the dynamic response analysis of a base-isolated building, the equivalent damping factor Heq and stiffness Kh are most important parameters. In this paper, all characteristics are evaluated by these two parameters. Kh=1.163kN/mm and Heq=0.272 were calculated from the hysteresis loop shown in Fig.7.

On the other hand, the yield load and the post-yield stiffness, which are directly related with property of materials used in the bearing, are widely used in the design model. The yield load is defined as yield point of the lead plug, and post-yield stiffness is defined as stiffness of rubber bearing shown in Fig.7. The hysteresis loop shown in Fig.7 was a combined loop of the lead plug and the rubber bearing.

3.2.2 Shear failure test

A monotonic shear failure test was performed using a φ200 specimen. Due to the limit of the test machine, a maximum shear strain 435% was performed. At the maximum strain, the specimen has no visible damage. The hysteresis loop is shown in Fig.16. Since the diameter of the specimen is 200mm, there was no overlapped area when the strain become 435% or by the displacement of 210mm.

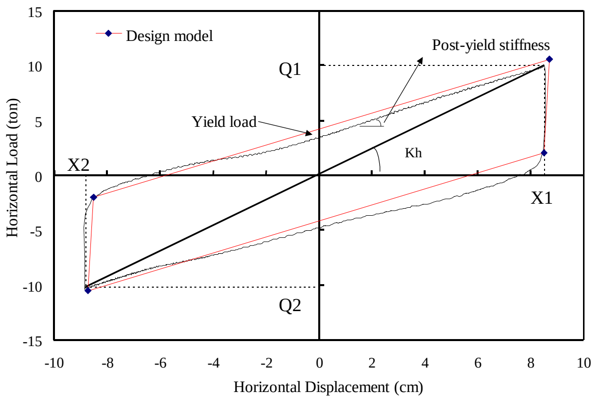

Fig.7: Comparison between horizontal load displacement hysteresis loop and the design model.

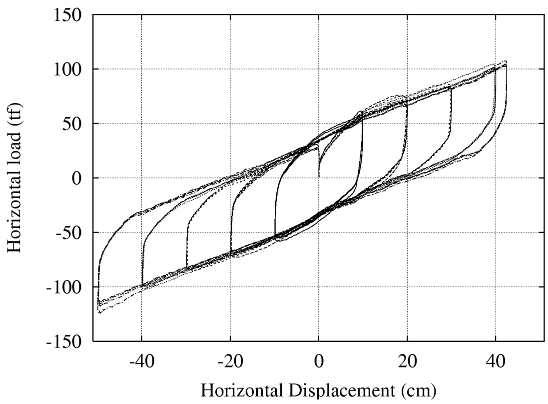

Fig.8: Horizontal load displacement hysteresis of a φ1000 (50%~250%) type specimens under axial stress of 10MPa.

3.2.3 Real size specimen test

φ600~φ1000 type lead rubber bearings were developed to use in Japan. The details of φ800 and φ1000 type are shown in Table 1. Typical shear test result of a φ1000 type specimen is shown in Fig. 8.

3.3 Dependence Tests

Since lead rubber bearings are main structural elements, the modeling concerned them in the dynamic response analysis becomes very important. In addition to the basic characteristics, various dependence properties are discussed here.

3.3.1 Shear strain dependence

Damping factor and equivalent stiffness under the design stress of 10MPa with the shear strains of γ=±10, 25, 50, 75, 100, 125, 150, 175, 200% were calculated from the tests of ϕ400 type lead rubber bearings. Values normalized to those at the shear strain γ=100% are shown in Fig.9. Damping factor and equivalent stiffness decrease as the shear strain increases. Dependence on shear strain was strongly observed, especially within small shear strain range. A modified bilinear model should be considered in the dynamic response analysis.

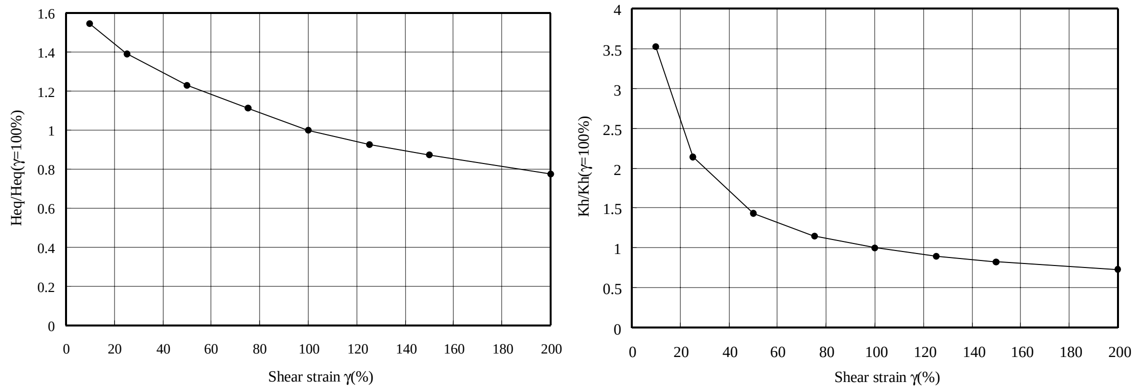

Fig.9: Damping factor (left) and equivalent stiffness (right) under the design stress of 10MPa with the shear strains of γ=±10, 25, 50, 75, 100, 125, 150, 175, 200%. Values were normalized to those at the shear strain γ=100%.

3.3.2 Fatigue test

As part of a building, lead rubber bearings have to survive a number of earthquakes. The energy in an earthquake is also considerable. Fatigue test of a ϕ400 specimen was dynamically tested at shear strains of 50% and 100% for a total of 200 cycles. The shear strain of 100% usually occurs under a level I earthquake proposed by Building Center of Japan. All damping factor and stiffness values were analyzed from the hysteresis loops with the shear strain of 100%. Their decrease ratio to the value of the 3rd cycle is shown in Fig.10. Heq(50)/Heq(3)=0.9, Kh(50)/Kh(3)=0.85 were obtained.

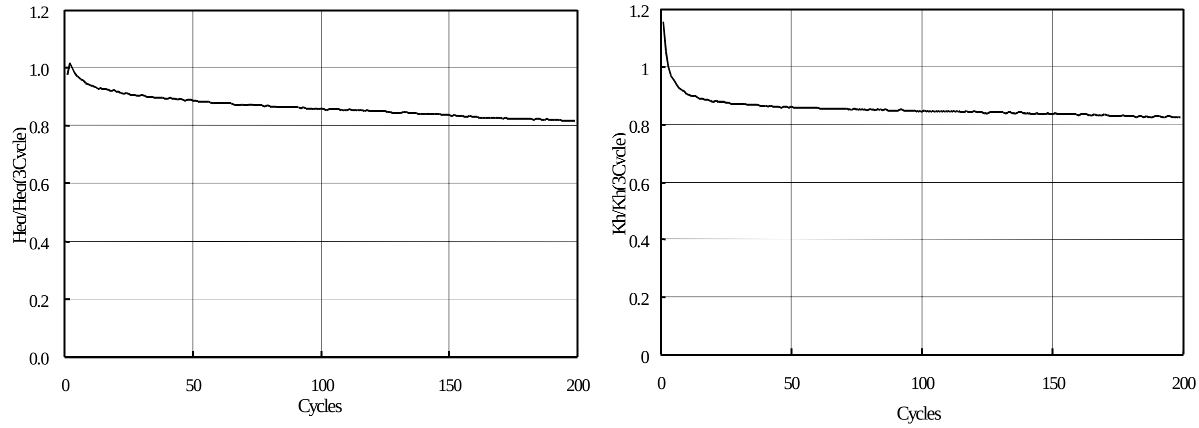

Fig.10: Decrease ratio for damping factor(left) and equivalent stiffness(right) in the fatigue test of a ϕ400 specimen. All values were normalized to the value of the 3rd cycle.

3.3.3 Vertical load dependence

The vertical load on the lead rubber bearing varies when an earthquake occurs. Effect of the vertical load on hysteresis loops over a range of σ=5,10, 15MPa was analyzed from the tests in section 3.2 and found to be very small. In Fig.11 values of damping factor and stiffness normalized to σ=10MPa is shown. The ratio values at the shear strain of 100% were as follows: Heq(50)/Heq(100)=0.9, Heq(150)/Heq(100)=1.09; Kh(50)/Kh(100)=0.99, Kh(150)/Kh(100)=0.98.

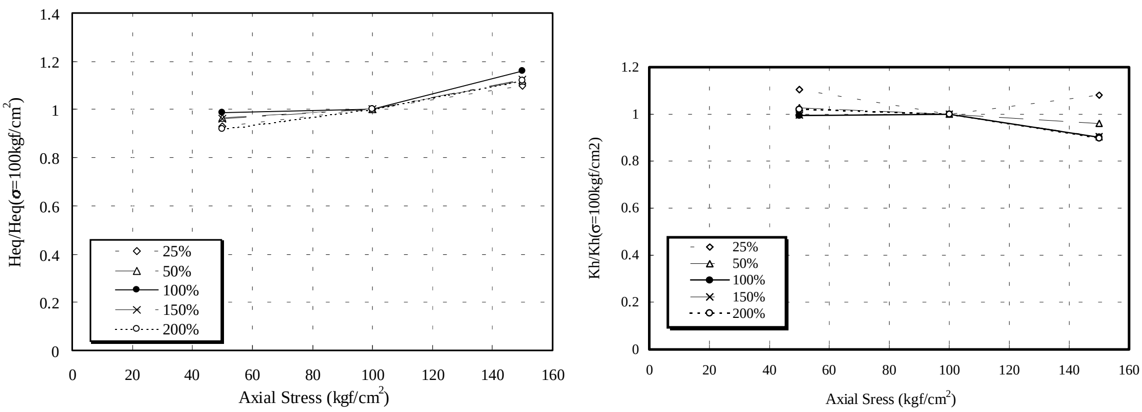

Fig.11: Values of damping factor (left) and stiffness (right) normalized to σ=10MPa. Effect of the vertical load on hysteresis loops over a range of σ=5,10,15MPa was analyzed.

3.3.4 Large shear deformation dependence

There are many different amplitude levels in an earthquake. The behaviors before and after a larger shear strain were tested. Hysteresis loops at strain of 100% before and after shear strain of 200% are shown in Fig.12, where outer loop is before, the shear strain of 200% and inner loop is after that. Little change was observed

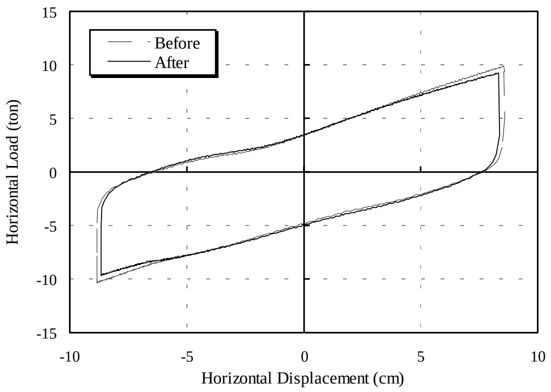

Fig.12: Hysteresis loops at strain of 100% before and after shear strain of 200%. Little change was observed.

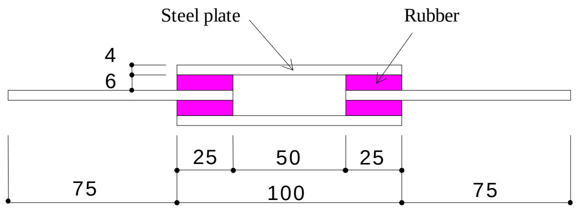

Fig.13: Test specimen recommended by JSSI (1996) used in the frequency and temperature dependence tests.

3.3.5 Frequency dependence

Loading speed of the test machine in a typical shear test is about 30mm/sec. Hysteresis loops under an earthquake, which has rich frequency components, should be tested. Due to the limit of test facilities, a test specimen recommended by JSSI(1996) which consist of 4 steel plates and 4 rubber plates shown in Fig.13 was used instead. The size of the rubber plate is 25*25*6mm (thickness).

Four specimens were evaluated as one set. The specimens were tested at a frequency range of 0.01, 0.1, 0.2, 0.5, 1.0Hz at shear strain of 100% without axial load. Stiffness values were calculated from the result of 3rd cycle in a total of 5 cycles. Stiffness values, which were average values of all four specimens normalized to the value at 0.5Hz, is shown in Fig.14. There was little change at the studied frequency range.

3.3.6 Temperature dependence

A rubber bearing should be tested to ensure its performance in extreme temperature environments. The test specimen shown in Fig.13 was used.

Four specimens were evaluated as one set. The specimens were tested at a temperature range of -20, -10, +20, +25, +40^{o}C without axial load. The test was performed using a 10KN autograph universal test machine, which has a chamber to keep a fixed temperature. The test started 60min later after the specimen was put in the chamber.

Stiffness at shear strain of 100% was calculated from the result of 3rd cycle. Stiffness values normalized to the value at 20^{o}C are shown in Fig.15. Although there was little change over 20^{o}C, the stiffness increased by +13% at -20^{o}C compared with that at 20^{o}C.

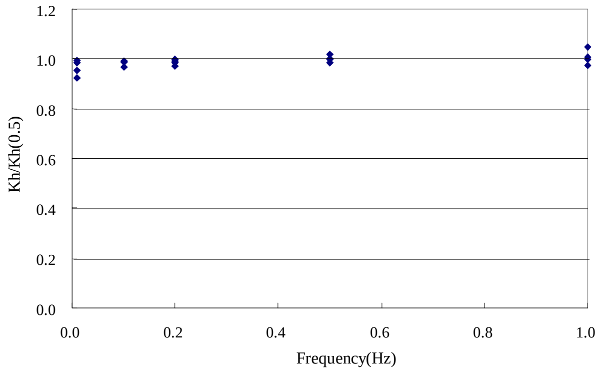

Fig.14: Stiffness values at a frequency range of 0.01, 0.1, 0.2, 0.5, 1.0Hz, which were normalized to the value at 0.5Hz.

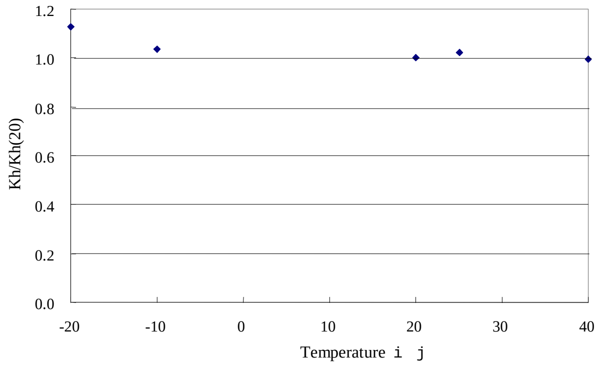

Fig.15: Stiffness values at a temperature range of -20, -10, +20, +25, +40°C, which were normalized to the value at 20°C.

3.4 Durability Tests

Since service period of a building is usually considered to be 60 years, rubber bearings should have enough safety also. 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's Theory. From the results of the raw rubber material test, it was found that the condition at a temperature of 85°C for 7 days corresponded using condition at a temperature of 25°C for 60 years for rubber bearings. All durability tests followed this condition.

3.4.1 Creep test

Rubber material is known to be very soft. An axial shrink of rubber bearings under design load is important since different shrinks will lead stress on other structural elements. A ϕ200 specimen was used to perform creep test to keep vertical load small enough. The Principle of Leverage was used in the creep test machine to keep an axial load constantly. The stress on the specimen was equal to the design stress of 10MPa.

In order to keep the temperature in the whole specimen to be uniform, pre-heating was conducted without axial load. The specimen was heated for 24 hours at condition 85°C first. Then the test was conducted instantly. Relative displacements between top and bottom in 4 corners were measured. The sampling time was as follows. For first 100 minutes, interval was 1 minutes. After 100 minutes, the interval becomes long gradually such as 10,30,60,180,360 min. After that the interval become 360min. The creep test lasted 7 days.

The result is shown in Fig.16. The vertical displacement does not include elastic deformation of the specimen. The creep is very small as much as 0.22mm or 0.22/48=0.5% by strain.

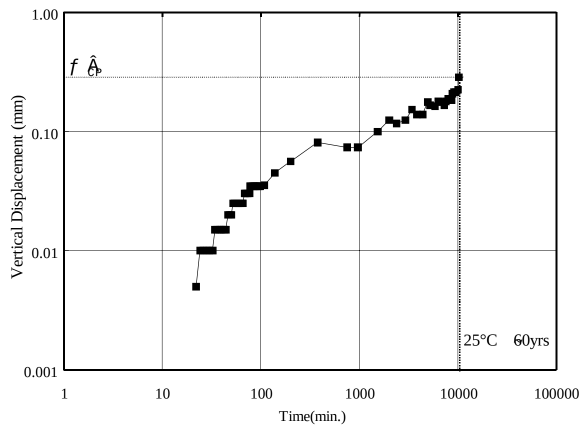

Fig.16: Creep of the specimen ϕ200 where elastic deformation was excluded.

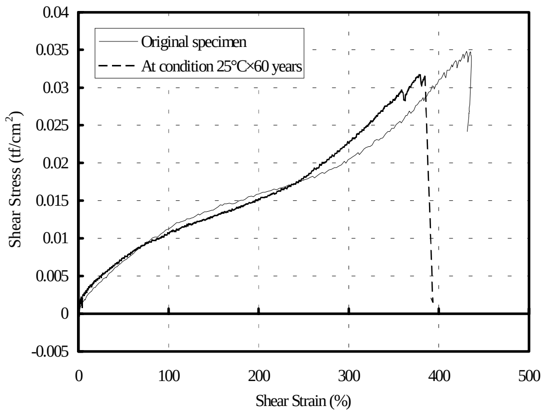

Fig.17: Shear failure tests. The ϕ200 specimen was tested up to the shear strain of 435% without visible damage. The specimen after heating corrupted at the shear strain of 380%.

3.4.2 Accelerated ageing test

Ageing of rubber material is known to be large. Changes in characteristics of rubber bearings after 60 years should be considered in the response analysis of the Building. Vertical stiffness and post-yield stiffness of a ϕ400 specimen was tested.

The specimen was taken out from the heating oven with a temperature of 85°C after 7 days. Then the specimen was cooled off for 24 hours naturally, to keep the temperature in the whole specimen uniform. The vertical stiffness test was performed by statically apply cyclic 10MPa±30% to the specimen. The horizontal stiffness test was performed with shear strain of 100% under compressive stress of 10MPa. From hysteresis loops, it was found that the vertical stiffness increased by +7%, the post-yield stiffness increased by +6% after 60 years service.

3.4.3 Shear failure test after 60 years service

The monotonic shear failure test was conducted using the ϕ200 specimen after the creep test to compare the result of the original one. The specimen corrupted at shear strain of 380%. The hysteresis loop is shown in Fig.17 with the result of the original one. The load displacement relation agrees well before shear strain 250%. After the shear strain of 250%, the specimen after heating becomes harder than the original one.

4. CONCLUSIONS

Chinese lead rubber bearings were tested followed the draft standard from Japan Society of Seismic Isolation (1996).

In vertical compression failure test of a ϕ200 specimen, the specimen stayed elastic until stress σ_{ec}=90MPa, and corrupted at stress of σ_{uc}=126MPa. In the tensile failure test, the specimen was found to stay elastic until σ_{et}=1.9MPa and corrupt at the tensile stress of σ_{ut}=3.5Mpa. Several kinds of shear test were performed used ϕ400 and ϕ200 specimens. A ϕ200 specimen was tested up to the shear strain of 435% without visible damage. A ϕ400 specimen was dynamically tested at shear strains of 50% and 100% for a total of 200 cycles in fatigue test. Compared with the value of 3rd cycle the stiffness of 50th cycle decreased by -15% while damping factor decreased by -10%. In the frequency dependence test, stiffness has little change at studied frequency range of 0.01, 0.1, 0.2, 0.5, 1.0Hz. In the temperature dependence test, the stiffness increased by +13% at –20^{o}C compared with that at 20^{o}C. Durability tests were performed to understand the characteristics of lead rubber bearings after 60 years service. The creep was found to be 0.22mm or 0.22/48=0.5% by strain for a ϕ200 specimen. From the accelerated ageing test of a ϕ400 specimen, it was found that the vertical stiffness increased by +7%, the post-yield stiffness increased by +6%.

Real size specimens of ϕ600~ϕ1000 type were tested. The typical shear test reults showed that both specimens have a steady load displacement hysteresis characteristics.

The test results showed that Chinese lead rubber bearing has been up to the standard of Japan Society of Seismic Isolation. Chinese lead rubber bearing has been proved to have good quality to use.

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