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A STUDY ON AGED DETERIORATION OF RUBBER BEARINGS INSTALLED IN THE ISOLATED BUILDING AFTER 30 YEARS IN USE

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Abstract

In recent years, many isolated buildings have been constructed. This is because the seismic safety of these buildings has been demonstrated in several major earthquakes. These buildings must be designed with consideration for variations in the characteristics of the seismic isolation devices, such as fluctuation of mechanical properties, temperature dependency, aged deterioration, and more. In particular, aged deterioration of rubber bearings is evaluated from the results of acceleration heat aging test. It's been more than 30 years since seismic isolation devices entered practical use in Japan. This means evaluations of their performance and verification of their durability over periods of up to several decades in actual use are not yet completed.

The authors have been carried out a series of experiments on the aging effects of laminated rubber bearings for 30 years using in an actual building which was first completed in Japan. This building is a four story RC structure with 25 natural rubber bearings and 12 sets of steel dampers as isolation devices. In these experiments, static loading tests and free vibration tests have been conducted using hydraulic jacks at the completion of this building in 1986, then in 1987, 2005 and 2016. The maximum deformation of 100mm, corresponding to the 100% shear strain of the rubber bearings, was adopted in every tests. After that, two bearings actually used were removed and horizontal sfiffness was measured. From these test results, the increase of horizontal stiffness of the bearings were estimated as almost 9% after 30 year usage under actual circumstances, within the range expected based on the results of the acceleration heat aging test. In addition, one removed bearing was subjected to a limit deformability test, and the other was tested for rubber material. From a limit deformability test, the bearing used for 30 years performed not lower than 350% strain before its crack. The limit deformability of laminated rubber bearings after 30 years remains in the similar level to that at the time of their production. From rubber material test results, it changed within about 30mm from the surface of the bearing to the center, but there was no significant change in the inner area. Compared with the rubber material test of the monitor specimen, the change of the rubber material actually used was almost equal to the change of the rubber material of the monitor specimen.

Through this research, it is confirmed that the natural rubber bearings use for 30 years maintain their characteristics of horizontal stiffness and deformation capacities sufficiently as were expected, and it is able to estimate aged deterioration of laminated rubber bearing for the most part from the monitor specimen.

Keywords: Isolated building; Natural rubber bearing; Aged deterioration; Free vibration test; Static loading test

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1. Introduction

It's been more than 30 years since seismic isolation devices entered practical use in Japan. This means evaluations of their performance and verification of their durability over periods of up to several decades of actual use are not yet complete. To predict the dynamic behavior of base-isolated structures during earthquakes, it is important to create appropriate models of the dynamic properties of seismic isolation devices. For conventional models, we use the properties obtained through loading tests with individual devices. But few studies have actually measured the dynamic and static properties of a seismic isolation device used in actual buildings.

The office building of the Technical Research Institute of Okumura Corporation was built 34 years ago as Japan's first practical base-isolated structure. At the completion, the authors conducted the experiments to verify the dynamic behavior of the building and the earthquake response observations have been carried out [1,2,3,4] .

This study has measured the shear stiffness and assessed the aged deterioration of the laminated rubber bearings in a static loading tests and a free vibration tests of this building. Additionally, we removed bearings from the building, and then performed a limit deformability testing of the bearing elements and a rubber material tests.

2. Outline of the target building and devices

The base-isolated structure tested in this study was built in September 1986 (Photo 1). The seismic isolation device consists of 25 natural laminated rubber bearings (NRB) and 12 sets of steel dampers. Table 1 provides the specifications of the target building and the seismic isolation devices. Fig. 1 shows the configuration of the seismic isolation devices.

Photo 1 – Target building

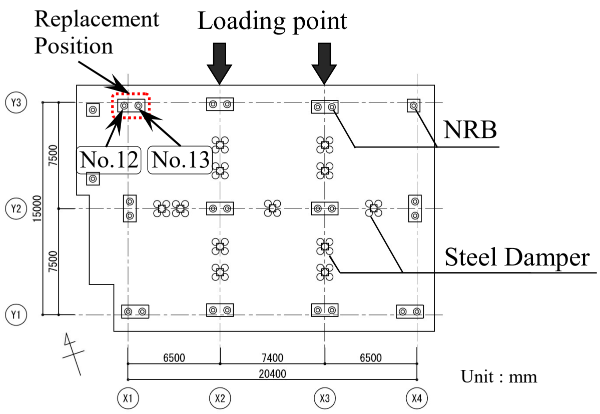
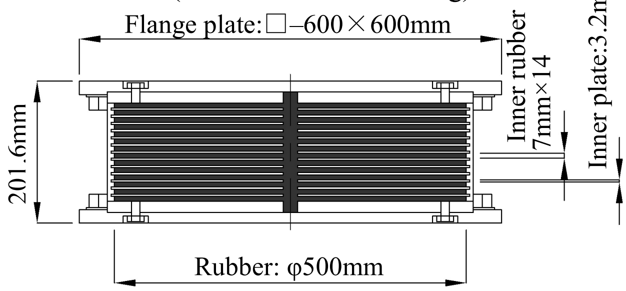


Fig. 1 – Plane of seismic isolation devices

Table 1 – Specifications of the target building and the seismic isolation device

		Specifications
Structure type		RC structure (4story) Base Isolation
Height		15.5m
Construction area		348.18m^2
Total floor area		1,330.1m^2
Seismic isolation device	Bearing	Natural Rubber Bearing φ500mm×25
	Damper	Steel damper φ50mm×12

NRB(Natural Rubber Bearing)



Primary shape factor S_1=17.1
Secondary shape factor S_2=5.1
Shear modulus G=0.44N/mm^2

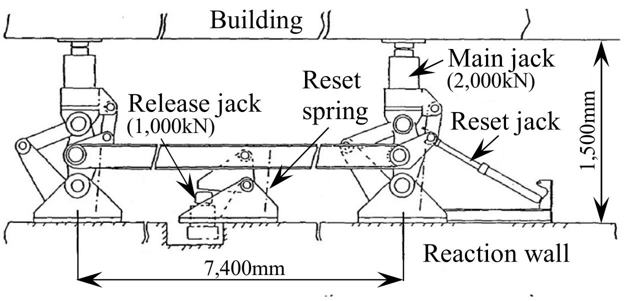
3. Aged deterioration of horizontal stiffness

3.1 Summary of the experiments on the aged deterioration of horizontal stiffness

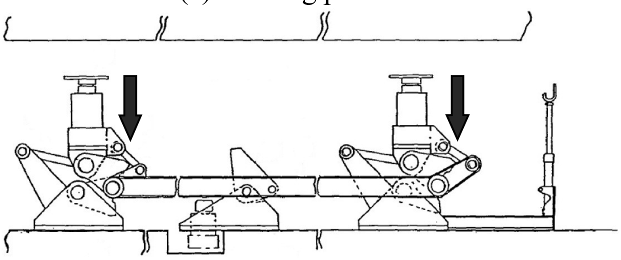
To evaluate the horizontal stiffness of the bearings installed in the building, we performed a static loading test and free vibration test while the steel dampers removed. We arranged a loading device with two hydraulic jacks attached between the building and the reaction body constructed on the north side of the building (Fig. 2) to apply loads to the north-south direction. We placed a displacement sensor in the building to measure the relative displacement of the upper structure and the foundation slab. We used the same loading device for testing at the time of its construction (Sept. 1986), in its 19th year (Sept. 2005), and in its 30th year (July 2016). Photo 2 shows the loading device. After the above three experiments, two bearings (No.12 and No.13 shown in Fig. 1,Photo 3) were removed. Horizontal stiffness of the removed bearings was measured on the same test machine(Fig. 3) as product inspection in 1986. Photo 4 shows the element performance test of the removed bearings.

3.1.1 Static loading tests in the target building

In the static loading tests, the load applied was defined to avoid exceeding a horizontal displacement of 100 mm (approximately 100% shear strain of bearing). We measured the load with load cells installed on hydraulic jacks. The horizontal displacement of the building was measured by a displacement sensor deployed at the point at which the load was applied.



(a) Loading position



(b) Release position

Fig.2 – Loading device of the building

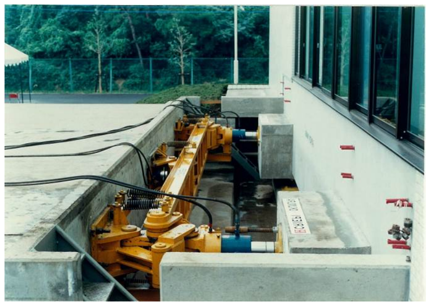


Photo 2 – Loading device installation

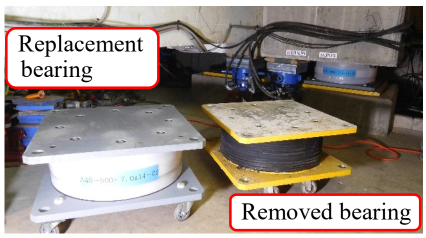


Photo 3 – Replacement of bearings

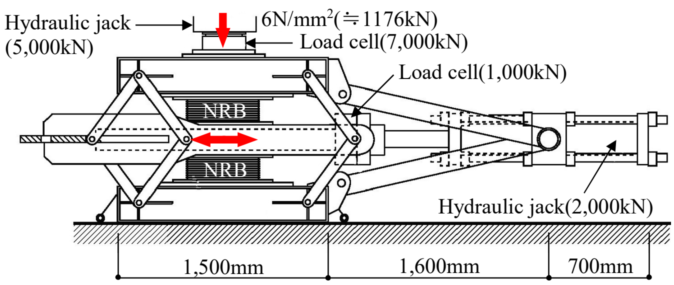


Fig.3 – Loading system of bearing element

Photo 4 – View of bearing element experiment

3.1.2 Free vibration tests in the target building

The free vibration tests were performed by first imposing the specified displacement (100 mm) into the building using the hydraulic jacks, then instantly releasing the load to allow the upper structure to vibrate freely. In addition to the load and horizontal displacement, we measured acceleration using an accelerometer installed on the first floor.

3.1.3 Horizontal performance test of the removed bearings

The horizontal load - deformation characteristics of the removed two bearings (No.12, No.13) were measured in pairs so that the horizontal load could be evaluated ignoring the friction of the test machine. Under a constant compressive stress of 6.0 N/mm^2 (=1176kN), the removed bearings were deformed ±200mm in one direction and loaded 3 cycles. Over the past 30 years, the static loading tests and the free vibration tests on the building have been performed multiple times in the same loading direction (North-South direction). In order to investigate the dependence on cyclic loading, tests were performed in two directions. One is the loading direction (North-South direction), and the other is the direction perpendicular to the building loading direction (East-West direction).

3.2 Results of the experiments

3.2.1 Static loading test

Fig. 4 shows the relationship between load and displacement in the static loading tests. All measured values of horizontal stiffness exceed the design value of 21.1 kN/mm. The values of horizontal stiffness measured in the displacement range of 50–70 mm, in which the change in stiffness of the bearings is small, were 22.0 kN/mm in both the 19th and 30th year, compared to 21.3 kN/mm at the time of construction. While the horizontal stiffness for the 19th year was 3 % greater than at the time of construction, the horizontal stiffness for the 30th year was the same as for the 19th year.

To evaluate the changes in the stiffness of the bearings at the respective displacements, we used a polynomial equation that approximated the relationship between displacement and load from zero to peak positive loading. Fig. 5 shows the secant stiffness at each measured value of displacement calculated with this equation. The figure shows that stiffness tends to decrease with increasing displacement in all years.

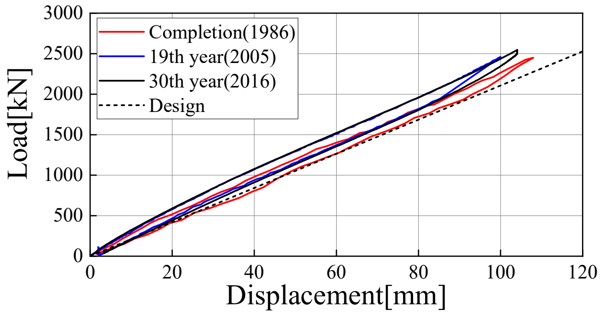


Fig.4 – Relation between load and displacement by static test

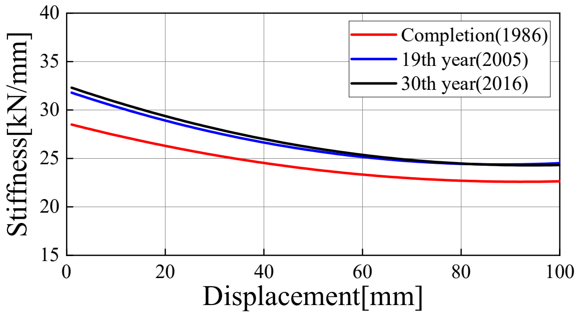


Fig. 5 – Stiffness of the laminated rubber bearings at each displacement

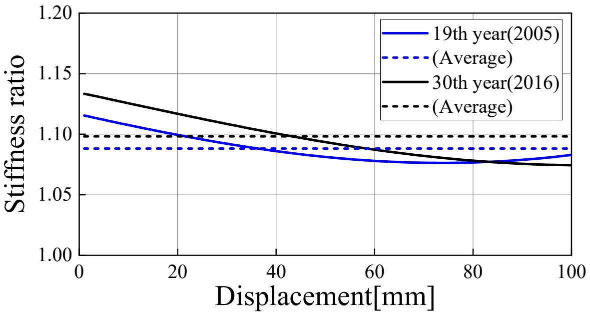


Fig. 6 – Stiffness ratio of the time of construction to aging

From the time of construction to the 19th year, stiffness generally increased; there was little change from the 19th to the 30th year. Fig. 6 gives the stiffness ratio at the time of construction and in the 19th year and the ratio at the time of construction and in the 30th year. We see that stiffness declines with increasing displacement. Calculations of the mean value of the ratio of stiffness to displacement in the displacement range of 0–100 mm gives a figure 8.7 % greater in the 19th year than at the time of construction, and a figure 9.7 % greater in the 30th year than at the time of construction.

3.2.2 Free vibration test

Fig. 7 shows the time history waveforms of displacement in the free vibration tests. To eliminate the effects of initial displacement, we measured the duration required for 10 cycles, excluding the initial cycle. At the time of construction, it took 18.48 seconds to complete the 10 cycles. At the 19th year, it took 17.83 seconds, or 3.5 % less time. In the 30th year after construction, it took 17.67 seconds, or 4.4 % less time than at the time of construction.

To evaluate changes in the stiffness of the bearings, we handled the base-isolated structure as one-mass-model. Calculations assumed that the period was equal to 1/10 of the time required to complete the 10 cycles and that the mass of the structure remains constant. The results of the calculations showed the horizontal stiffness of the bearings was approximately 7 % greater in the 19th year and approximately 9 % greater in the 30th year. To evaluate the changes in the stiffness of the bearings at each of the respective displacement levels, we determined the period and amplitude at each 1/2 cycle. Fig. 8 shows the changes in periods evaluated for each displacement amplitude. We see that the period becomes shorter with decreasing displacement. Despite some variations, the period at each amplitude in the 19th and 30th year is approximately 4 % shorter than at the time of construction.

Fig. 9 shows the change in damping ratio evaluated at each 1/2 cycle. For displacements of 60 mm or larger, the damping ratio h equals to 0.02; for smaller displacements, the damping ratio becomes larger with decreasing displacement. For displacement of 20 mm, our results indicate $h = 0.04$. The damping ratio of the bearings remains relatively unchanged over time.

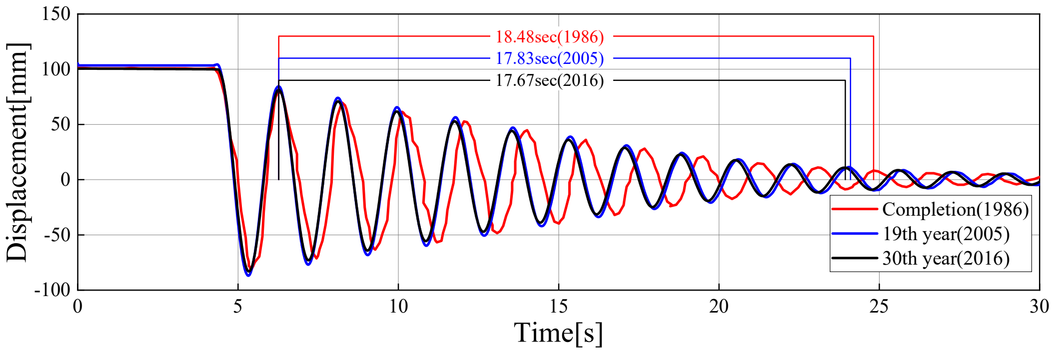


Fig. 7 – Time history waveforms of displacement (Free vibration test)

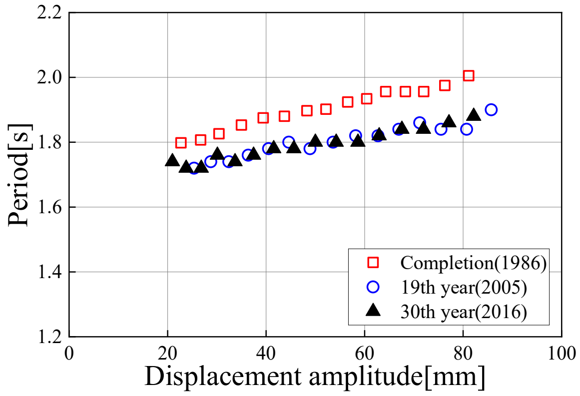


Fig. 8 – Comparison of period

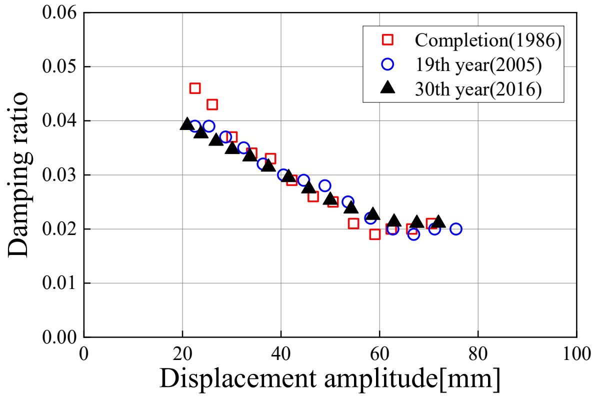


Fig. 9 – Comparison of damping ratio

3.2.3 Element performance test of the removed bearings

Fig. 10 shows a comparison between the histeretic curves of the bearings No.12 and No.13 at the time of product inspection conducted in 1986 and those of the same laminated rubbers actually used in a building for 30 years. The results of the 31st year showed that there was no difference depending on the direction, and there was also no cyclic load dependency. In addition, the secant stiffness evaluated at displacement of ±50mm was about 10% greater than at the time of manufacture. Similarly, the secant stiffness evaluated at displacement of ±100mm was about 12% greater. As the horizontal deformation increased, the rate of change in secant stifness tended to increase. In the displacement range of 10mm-200mm, the average value of the rate of change of secant stiffness increased by about 11%.

Fig. 11 shows the secant stiffness per laminated NRB evaluated from the static loading test, free vibration test of the building, and element test of the removed bearings. The displacement and secant stiffness evaluated in all tests show the same tendency.

3.2.4 Comparison with the predicted values for aged deterioration

In designing the present base-isolated structures, our predictions for aged deterioration in performance of the laminated rubber bearings on heat accelerating test results[5]. The heat accelerating test theory is built on the Arrhenius equation. In a structure like a laminated rubber bearing, which consists of laminated layers of rubber sheets and steel plates, the deterioration of rubber due to oxidation is believed to take place only at the surface of the rubber layer. It is assumed that this deterioration will not progress into the interior of the rubber. Two types of heat accelerating test was performed at the design stage: a heat accelerating test1 performed in air for the aging of the surface of the laminated rubber; and a heat accelerating test2 performed in a nitrogen atmosphere for the aging of the interior of the laminated rubber. The results show that the horizontal stiffness of the laminated rubber bearing will increase by a factor of 1.17 in heat accelerating test1(equivalent to 120 years) performed in air and by a factor of 1.11 in heat accelerating test2 performed in a nitrogen atmosphere.

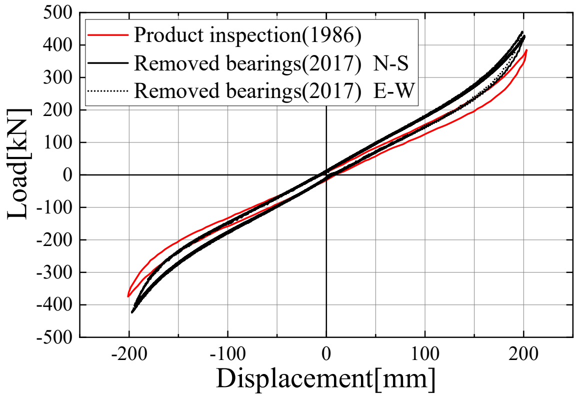


Fig. 10 – Relation between load and displacement of removed bearings(3rd cycle)

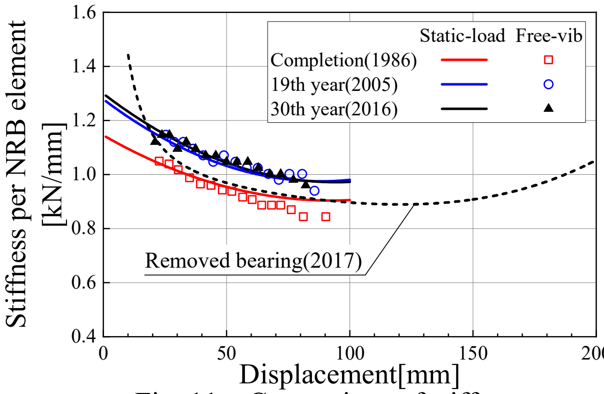


Fig. 11 – Comparison of stiffness

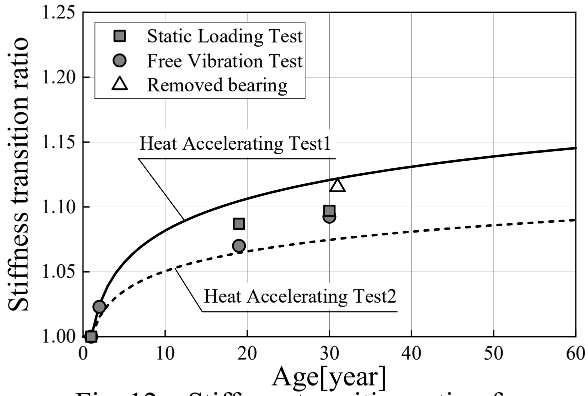


Fig. 12 – Stiffness transition ratio of age deterioration

Fig. 12 compares the rate of change in stiffness due to aging obtained from the loading test on the building, element test and the rate of change in stiffness predicted from the heat accelerating tests. The rate of change in horizontal stiffness due to aging obtained based on the results of the static loading test, free vibration test on the building and element test based on removed bearings falls somewhere between the values predicted by heat accelerating test1 and test2. This confirms that the horizontal stiffness remains within the range anticipated at the time of construction and that the design retains a sufficient margin of safety with respect to the rate of change in stiffness, the maximum design value of which is 17 %.

4. Limit deformability test of the NRB element

4.1 Summary of the experiments

We removed two bearings from the building (Photo 3) to examine the limit deformability in a compression shear test machine. Fig. 13 is a schematic drawing of the loading system. This system is equipped with two and four actuator units in the horizontal and vertical directions, with a loading capacity of 6 MN and 25 MN, respectively. The sum of the values of the load cells for each direction is considered to be the load; the mean value of the values measured by displacement sensors in each direction is regarded as displacement. The direction of load application is set to coincide with the direction of displacement of the building in the loading test. Table 2 shows the loading history. A bearing stress of 6.0 N/mm^2 corresponding to a design load of 1,176kN on the building is regarded as the vertical load; displacement corresponding to shear strain of γ = ± 100 %–±400 % relative to the total thickness of rubber is regarded.

Table 2 – Loading hystory

Shear strain γ [%]	Velocity [mm/s]	Cycle
±100	5	3
±153		
±200		
±250		
±300	3	1
±350		
±400		

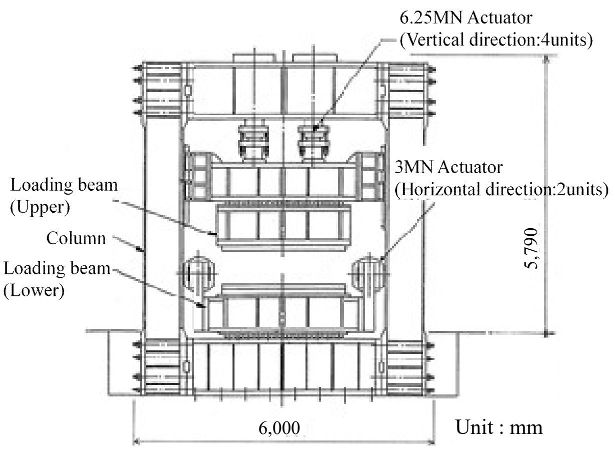


Fig. 13 – Loading system

4.2 Results of the limit deformability tests

Photo 5 shows the external views of the bearing during testing. Fig. 14 illustrates the relationship between horizontal load and horizontal deformation. No anomalies are observed in the rubber up to γ = ±300 %. At the load of γ = ±350 %, a crack appears in the 45° direction relative to the direction of load application; however, no decrease in horizontal load is observed, and the vertical force remains stable. A similar trend continued to be observed at γ = ±400 %. Due to the propagation of the crack, the test was closed because the limit deformability was confirmed. Note that a crack had also appeared on the side opposite to that shown in Photo 5; this propagated along the perimeter. Less significant cracks were also visible near the point of perpendicular load application on the topmost rubber layer. A limit deformability test was performed 30 years ago on a NRB having the same specifications as the bearing tested in the present study[6]. Fig. 15 compares the results of the two tests on the relationship between the shear stress and shear strain. The results confirm that a deformation capacity of γ = 370 %, comparable to the value 30 years ago, remains.

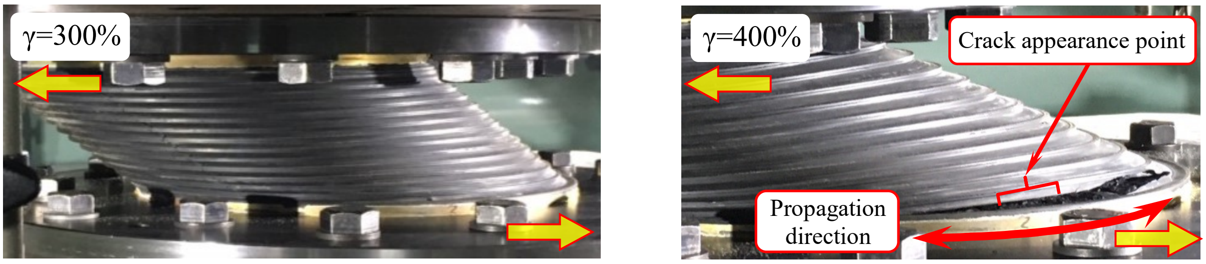


Photo 5 – Extrenal views of the NRB(γ=300%, 400%)

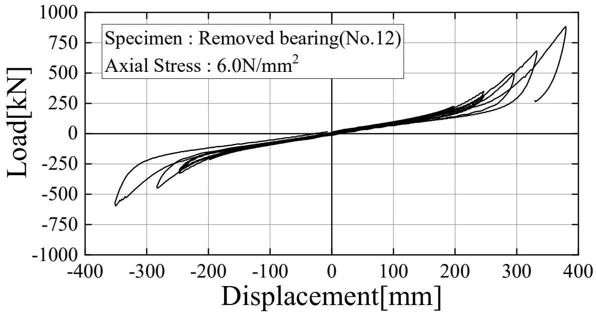


Fig. 14 – Hysteretic curve

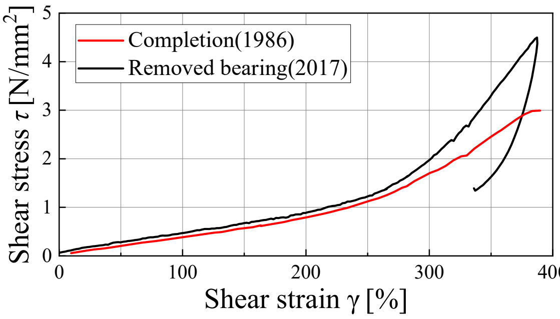


Fig. 15 – Comparison in deformability

5. Rubber material properties of NRB actualy used in 30 years

5.1 Summary of the experiment

In order to investigate the rubber material of the removed bearing, the rubber material of the No. 13 bearing was cut out. Rubber materials were measured for hardness, tensile and shear performance. In the same way, the tensile and shearing properties of the monitor specimen were measured, and compared with the rubber materials of the removed bearing.

5.1.1 Rubber material test of removed bearing

Fig. 16 shows the positions of rubber specimen cut from the removed bearing. For the dumbbell test pieces, the 8th layer of the removed bearing rubber was cut into a dumbbell-shaped No. 3 (JIS K 6251). The shear specimens were cut from the 4th, 6th and 8th layers rubber and upper and lower intermediate steel plates of the removed bearing. The rubber sheet was cut from the 13th layer of the removed bearing into 470 mm × 40 mm. The measurement pitch of the international rubber hardness was 2.5 mm intervals in the range of 50 mm from the outermost edge and the center, and 5 mm or 10 mm intervals in the others.

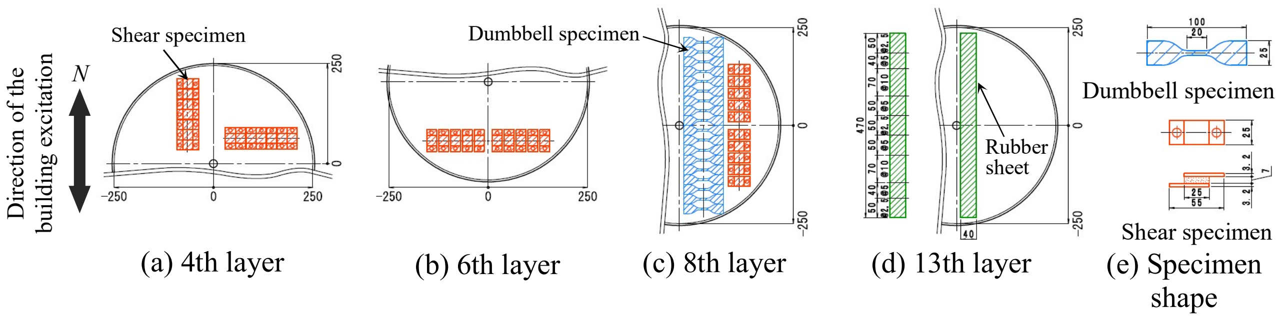


Fig. 16 – Position of rubber specimen cut from the removed bearing

5.1.2 Rubber material test of monitor specimen

The monitor specimen has been stored at a compressive stress of 6.9N/mm^2, equivalent to long-term compressive stress. Fig. 17 shows the positions of rubber speciment cut from the monitor specimen. The monitor specimen was cut out in 1997, 2007, and 2016. In the investigation of rubber properties of the monitor specimen, hardness, tensile strength at 100% strain, tensile strength at break, and elongation at break were evaluated from dumbbell test pieces. The bearing after cutting was coverd with a protective rubber provided.

5.2 Results of rubber material test

5.2.1 Results of rubber material test on the removed bearing

Fig. 18 shows the measurement results of the dumbbell specimen. The horizontal axis indicates the distance from center of the bearing. The result of rubber hardness at each position exceeded the standard value at the time of manufacture by about 10%, and particularly increased near the outer part of bearing. Also, the result of tensile strength at 100% strain was about 15 to 25% larger than the other measurement points in the range of about 30 mm from the outer part of rubber. All results of tensile strength at break exceeded the standard value of manufactured, and on average were about 30% greater than the standard value. The elongation at break results tended to be lower than the manufacturing standard. Fig. 19 shows the measurement results for the shear specimen. Although the measurement results showed large variations, the shear strength at 100% strain and the shear strength at break increased from the center to the outside, and the shear strain at break tended to decrease from the center to the outside. It is considered that the variation in the results is cased by the variation in the shape of the shear specimen. The International Rubber Hardness Degree(IRHD) of the

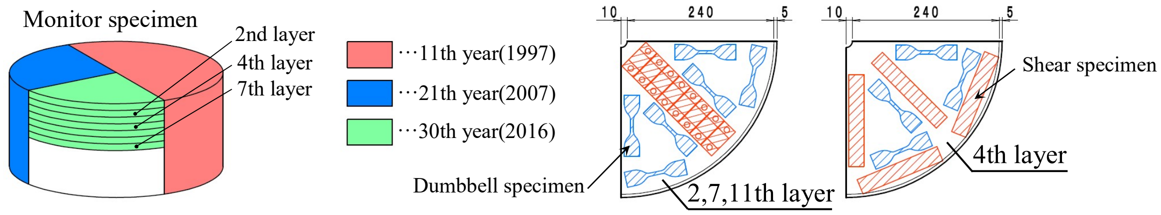
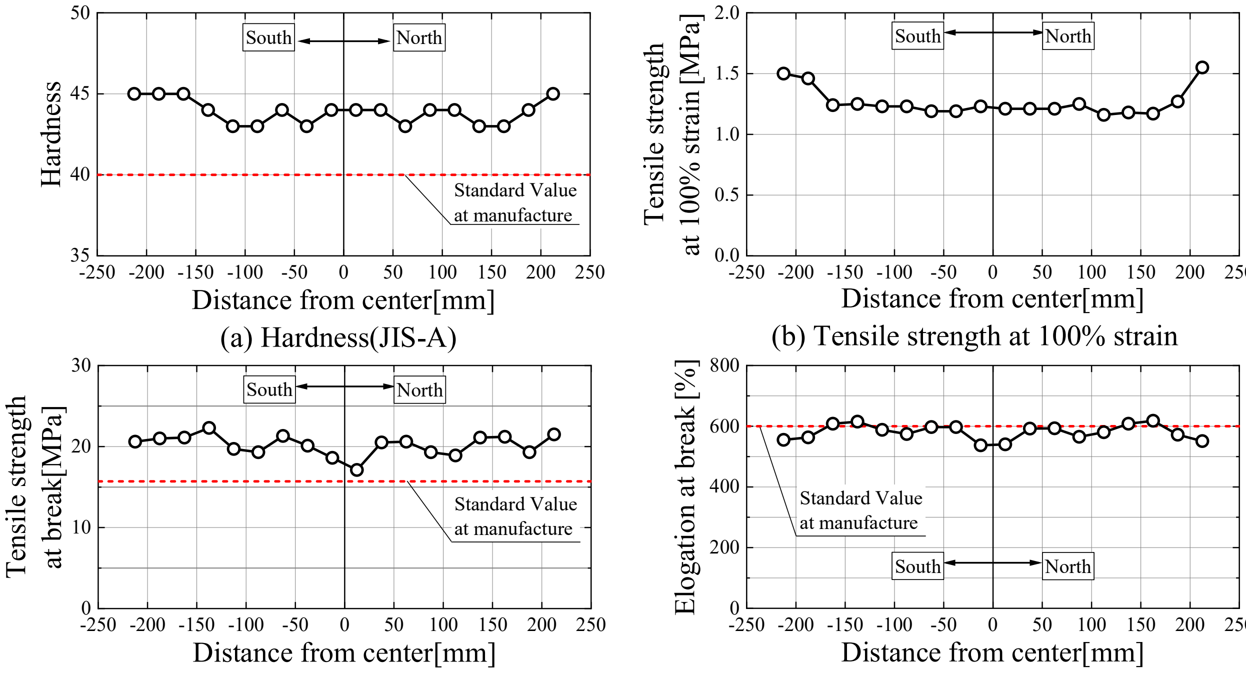


Fig. 17 – Position of rubber specimen cut from the monitor specimen



(a) Hardness(JIS-A)

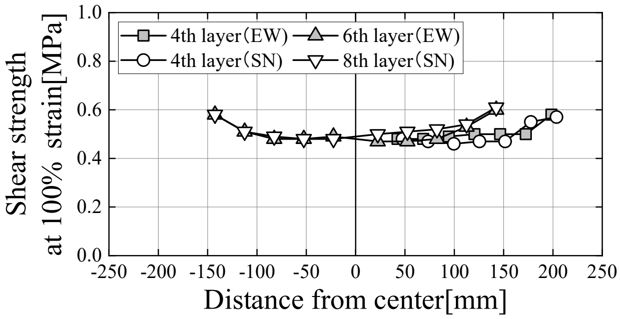
(b) Tensile strength at 100% strain

(c) Tensile strength at break

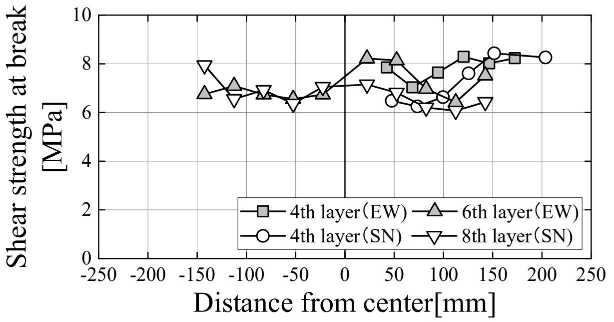
(d) Elogiation at break

Fig. 18 – Results of dumbbell specimen(8th layer in the removed bearing)

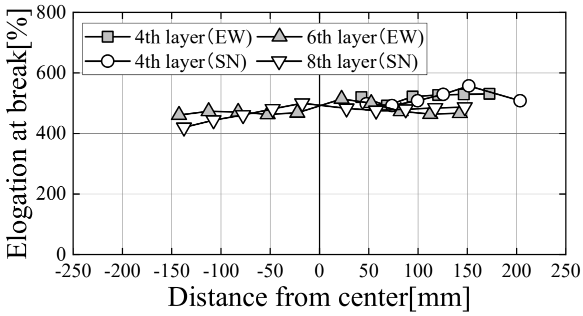
rubber sheet shown in Fig. 20 indicated the same tendency as the rubber hardness of the dumbbell specimen, and the outer peripheral portion about 50mm tended to be larger than other measurement points. Becase the rubber sheet specimen is the outer layer of the dumbbell specimen, the hardness of the rubber sheet may be lager than that of the dumbbell specimen, but the difference in the measurement method may have an effect.



(a) Shear strength at 100% strain



(b) Shear strength at break



(c) Elogation at break

Fig. 19 – Result of shear test specimen

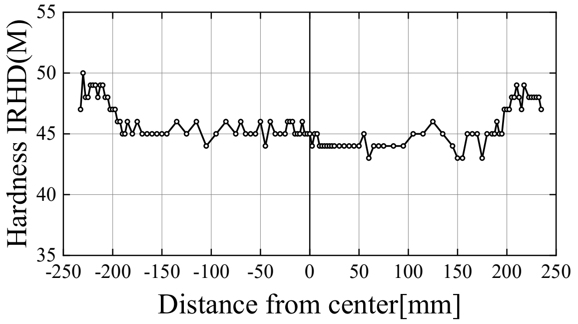
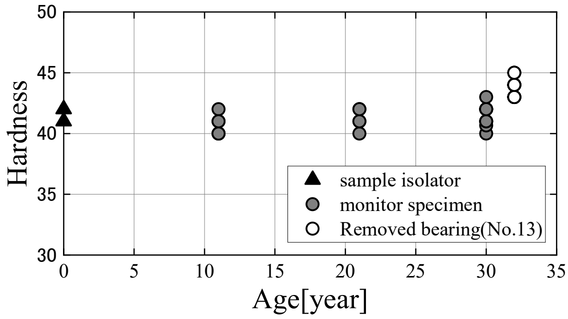
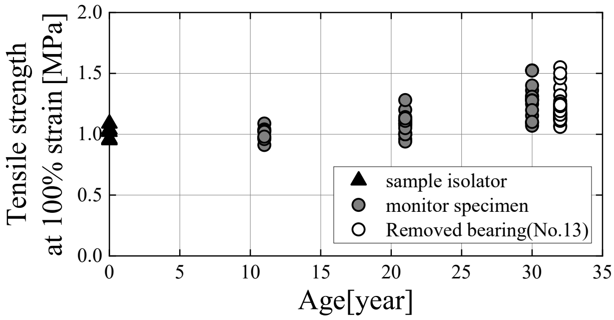


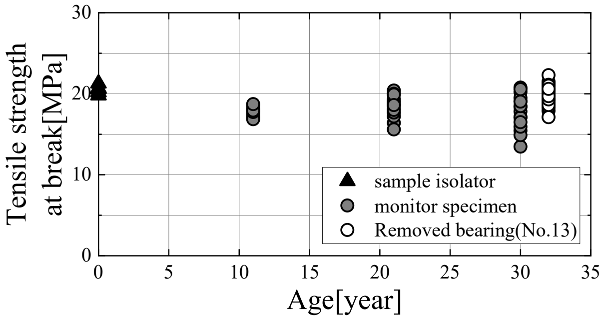
Fig. 20 – Result of rubber sheet specimen



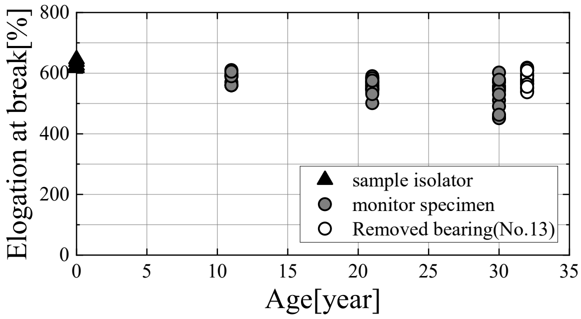
(a) Hardness(JIS-A)



(b) Tensile strength at 100% strain



(c) Tensile strength at break

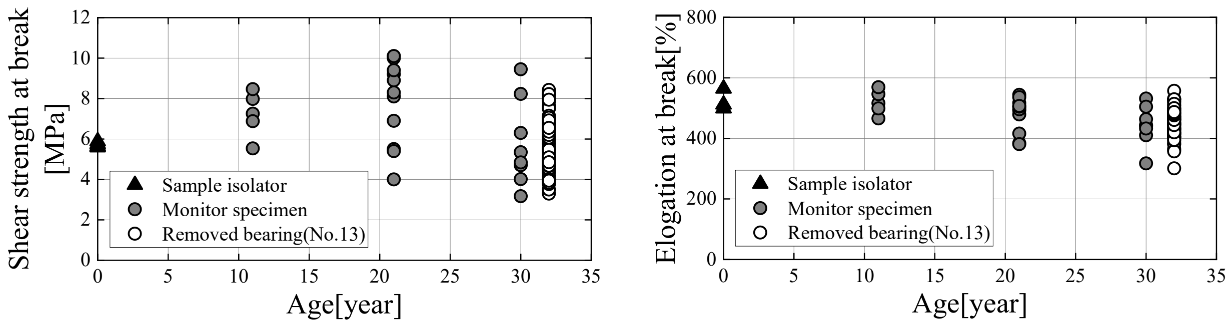


(d) Elogiation at break

Fig. 21 – Comparison of dumbbell test results

5.2.2 Comparison of material properties of removed bearing and monitor specimen

Fig. 21 shows a comparison of the dumbbell test results for the monitor specimen and the removed bearing. The average value of rubber hardness and tensile strength at 100% strain gradually increased over the age. And the average values of tensile strength at break and elongation at break tended to decrease. Variations in all material test results increased over the age. Due to individual differences of the NRB itself, it cannot be clearly mentioned, but the results of monitor specimen at 30th years and the removed bearing actually used 30th years showed approximately the same averages and variances. Fig. 22 compares the results of the shear test results between the monitor specimen and the removed bearing. The material properties obtained from the shear specimen showed the same tendency as the results of the dumbbell specimens and were highly variable. This is considered to be due to the variation of the shear specimens. From the results, it is considered that the aged deterioration of NRB installed in the isolated building can be evaluated from the monitor specimen.



(a) Shear strength at break (b) Elogation at break

Fig. 22 – Comparison of shear test results

6. Conclusions

We investigated the changes in the performance of the laminated rubber bearings over time in a base-isolated structure for which 30 years have passed since construction. Our findings were as follows.

< Static loading test, free vibration test of the building, and horizontal performance test of the removed bearing >

i. The results of static loading tests show that the horizontal stiffness of the bearings increased by approximately 9 % by the 19th year and by 10 % by the 30th year after construction.

ii. The results of a free vibration tests show that the horizontal stiffness of the bearings increased by approximately 7 % by the 19th year and by approximately 9 % by the 30th year after construction.

iii. The results of a free vibration tests show no significant change in the damping performance of the bearings by the 19th and 30th year compared to that at the time of construction.

iv. The results of unit test of the removed bearings show that the horizontal stiffness increased by approximately 11% by the 31th year compared to that at the time of manufactured.

v. The rate of change in the horizontal stiffness of the bearings determined based on the results of the static loading test, free vibration test and element test of the removed bearings remains within the range expected based on the results of acceleration heat aging test.

< Limit deformability test >

vi. The limit deformability of bearings after 30 years remains at levels similar to those at the time of construction.

< Rubber material tests >

vii. The rubber material test results of the removed bearing after use for 30 years changed within a range of about 30 mm from the surface toward the center, but there was no significant change.

viii. The results of the material tests of monitor specimen show the aged deterioration of bearings installed in the isolated building can be evaluated.

These findings confirm that the bearings retain the required performance even after 30 years in use. In the future, we plan to carry out a loading test of the building every 10 years.

7. References

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