LONG TERM TESTS FOR CREEP OF LAMINATED RUBBER BEARINGS

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SUMMARY

The laminated rubber bearing is the most important structural member of a seismic isolation system. The basic characteristics of rubber bearings have been confirmed by compression tests, compressive shearing tests and creep tests. This paper presents the results and analysis of creep tests conducted on full-scaled laminated rubber bearings under axial stresses of 110kg/cm^2, 150kg/cm^2(about 2 years) and 200kg/cm^2(about 5 years, on going) at our laboratory. These tests indicate that the maximum creep deformation is about 0.2-0.6% of total rubber thickness.

INTRODUCTION

The basic performance of laminated rubber bearings, which are an important structural member of a seismic isolation system, has been confirmed by full-scale tests such as compression tests and compressive shearing tests, and they are actually being used in buildings. When considering the durability of the laminated rubber bearing, the review of ageing caused by oxidation of the rubber layers and creep deformation caused by axial compressive force over long periods of time becomes important. It has been confirmed from inspections of rubber pads which have been actually used for 100 years[1] and accelerated thermal degradation tests[3, 4] that the structure of the laminated rubber bearing is such that the oxidation of the rubber progressed from the surface of the rubber sheets, and only has an influence to a depth of several mm from the surface. A coating rubber has also been added around to protect the inside of the laminated rubber bearing from external factors such as oxygen and ultraviolet light, and this reduces the influence of oxidation even further. However, the slight changes in the stiffness and deformability of the laminated rubber bearing caused by ageing of the physical properties of rubber should be taken into account in designing.

With regard to the assessment of the creep properties of the laminated rubber bearing, two year creep tests (under axial compressive stress of 110 kg/cm^2 and 150 kg/cm^2) have been carried out using two types of the laminated natural rubber bearing[1, 2]. The results of the tests predict that the creep deformation in 100 years' time to be within several mm, leading to the observation that the creep deformation of the laminated rubber bearing can be ignored in designing. The compression tests and compressive shearing tests conducted before and after the creep tests. These produced the result that the two year creep tests have negligible influence on the hysteresis of the laminated rubber bearing[2]. In order to realize high-performance seismic-isolated buildings, however, it is also necessary to clarify the creep properties of the laminated rubber bearing under high axial compressive stress. This paper therefore shows the results of creep tests carried out approximately 5 years (42,551 hours) using laminated natural rubber bearing under a constant axial compressive stress of 200 kg/cm^2. It also compares these results with past test results carried out under axial stress of 110 kg/cm^2 and 150 kg/cm^2 and discusses the influence on the creep behavior caused by the differences in axial stress and shape of laminated rubber bearing.

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TEST SPECIMENS

Table 1 gives an overview of three specimens used in this study, while Table 2 lists the basic components of rubber. Although different specimens had different content, natural rubber was the major component for all the specimens. The laminated rubber was about 500mm in diameter and the secondary shape factor was $S_2 \cong 5$. Only the 445X4-25 was covered by vulcanized natural rubber of 5mm thickness, and the others were laminated rubber whose steel plates were exposed. Figure 1 shows 500X3.75-26 specimen.

EXPERIMENTAL METHOD

Photo 1 shows the conditions of the experiment. A hydraulic jack, load cell and specimen were placed in a steel gate-type frame in the laboratory, and a constant compressive load was provided by a hydraulic pump. The 500X3.75-26 specimen was placed in the test frame, where it was subjected to a load of 400 ton (axial compressive stress of 200kg/cm^2; Photo 2). The 445X4-25 specimen was stacked on the 500X7-14 specimen and subjected to a load of 225 ton (axial compressive stress of 110kg/cm^2 and 150kg/cm^2; Photo 3). The fluctuation of the compressive load was within 3%. Since this experiment was designed to simulate actual conditions, the room temperature was not artificially controlled. The vertical deformation of the specimens was measured with 4 high-sensitivity displacement transducers that were placed between the fitting flanges of each specimen. The vertical deformation in this study is the average of the values recorded at the 4 locations. The compressive load was measured with a load cell. The temperature near the specimen (air temperature), as well as the temperature at a depth of 1cm from the surface of the rubber lamination (rubber surface temperature) were measured with a thermocouple. Measurements have been taken at hourly intervals over a period of about 2 years.

Table 1 Overview of laminated rubber bearings

Specimen	Diameter (D)	Rubber thickness (t_R)	Number of layers (n)	S	S	Axial stress	Shear modulus G	Measuring period	Measuring time
500×3.75-26	500mm	3.75mm	26	33.3	5.1	200 kg/cm^2	4.50 kg/cm^2	Aug. 24, 1994 July 2, 1999	42,551 hours
500×7-14	500	7	14	17.9	5.1	110	4.25	Oct. 27, 1987 Oct. 30, 1989	17,300
445×4-25	445*	4	25	27.2	4.5	150	5.26		

* Thickness 5mm of a protection rubber layer is inclusive S_1:Primary shape factor S_2:Secondary shape factor

Table 2 Basic component of rubber

Specimen	Natural rubber	Carbon black	Vulcanizing agents	Additives
500×3.75-26	76	14	3	7
500×7-14	55	18	3	24
445×4-25	68	18	2	12

(weight ratio %)

Primary shape factor :

$$S_1 = \left\{ \pi \cdot \left(\frac{D}{2} \right)^2 \right\} \Big/ \left(t_R \cdot D \cdot \pi \right) = \frac{D}{4t_R}$$

Secondary shape factor :

$$S_2 = \frac{D}{n \cdot t_R}$$

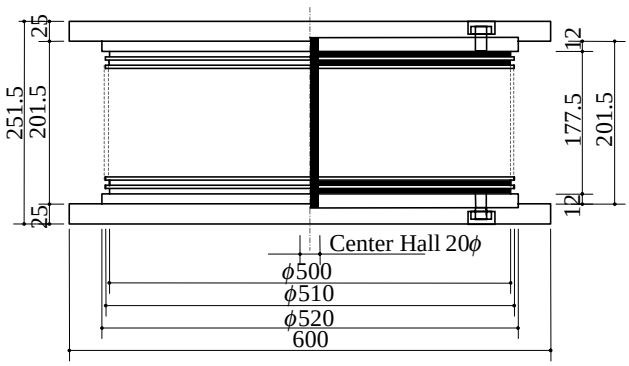


Figure 1 500X3.75-26 specimen

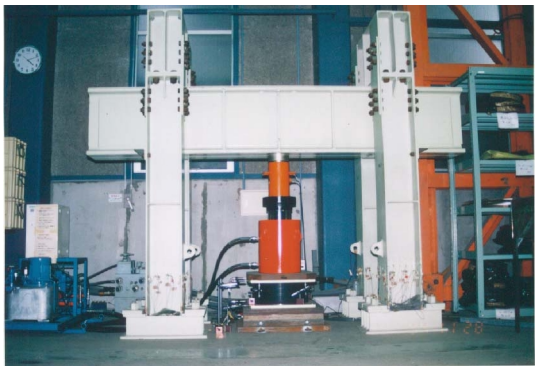


Photo 1 Conditions of the Creep experiment

EXPERIMENTAL RESULTS

Figures 2 and 3 show changes in the vertical deformation starting immediately after the placement of the design compressive load, and the change in air temperature. The vertical deformation in these figures is the relative deformation between the laminated rubber flanges. This value decreased as the laminated rubber expanded. Vertical deformation accompanied temperature change, and the rubber began to repeatedly expand and contract. The rubber surface temperature usually corresponded with the external temperature.

Since the measured values of this vertical deformation were affected to some extent by changes in temperature and compressive load, they were corrected using equation (1). The thermal coefficient in this equation was derived from the relationship depicted in Figure 4 between the rubber surface temperature and the vertical deformation corrected for the fluctuation of the compressive load. The 500X3.75-26 specimen had a constant temperature gradient through the time that the measurements were taken. However, in the case of specimens 500X7-14 and 445X4-25, five different periods of temperature gradient appeared, so thermal coefficients had to be derived for each period. These coefficients are listed in Table 3.

$$y = y' - \Delta P / Kv_{(ex)} - \Delta T \cdot \alpha - y_0 \qquad (1)$$

Here, y is creep (mm), y' is vertical deformation (mm), y_0 is the initial vertical deformation (mm), ΔP is deviation from the original design compressive load (ton), ΔT is the temperature difference from the initial rubber surface temperature ($°C$), and α is the thermal coefficient derived from the relationship between the rubber surface temperature($mm/°C$), the vertical deformation corrected for the fluctuation of the compressive load and $Kv_{(ex)}$ is the vertical stiffness derived from compression tests :

500X3.75-26 : 213.5 ton/mm
500X7-14 : 119.4 ton/mm
445X4-25 : 130.3 ton/mm

Creep values derived based on equation (1) are shown in Figure 5. Despite the fact that specimen 500X3.75-26 had a higher axial stress than specimens 500X7-14 and 445X4-25, it still showed the lowest creep, which was within 0.15mm after about 18,000 hours (2 years). And it was about 0.2mm after 43,000 hours (about 5 years). This was likely because specimen 500X3.75-26 contained about 76% natural rubber and relatively few artificial additives. At the same time, the primary shape factor was large so the vertical stiffness was high. Since the structure was apparently rigid, this likely helped to suppress creep.

Photo 2 500X3.75-26 specimen

Photo 3 445X4-25 specimen (Upper), 500X7-14 specimen(Lower)

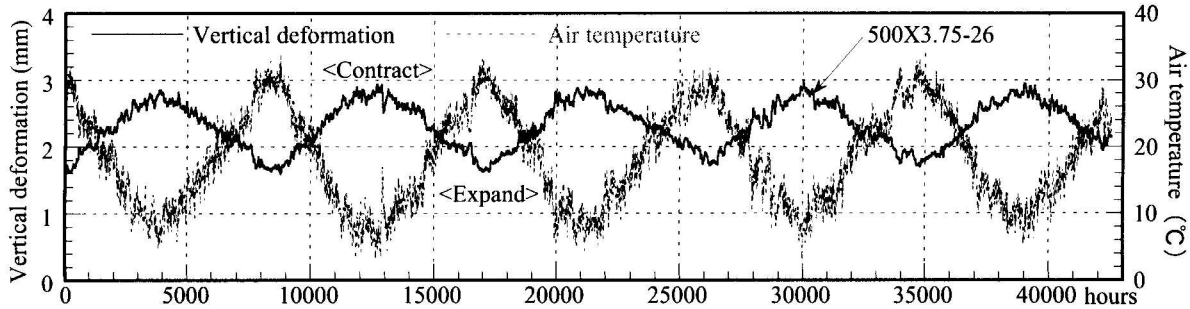


Figure 2 Changes in the vertical deformation and air temperature (500X3.75-26 specimen)

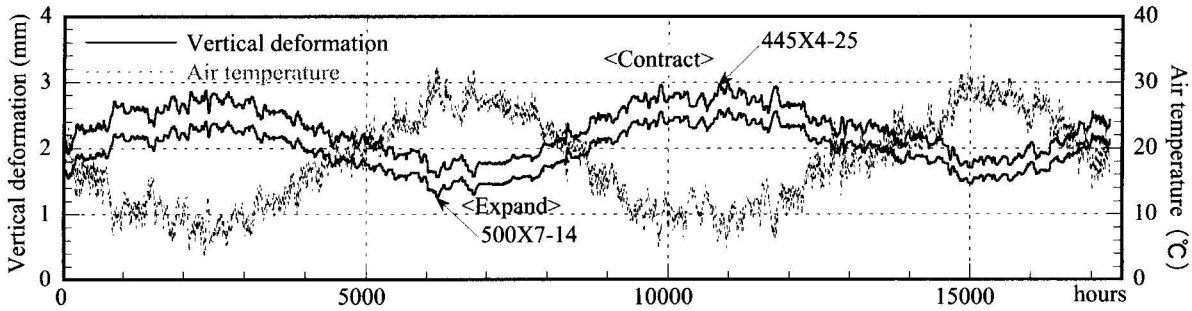
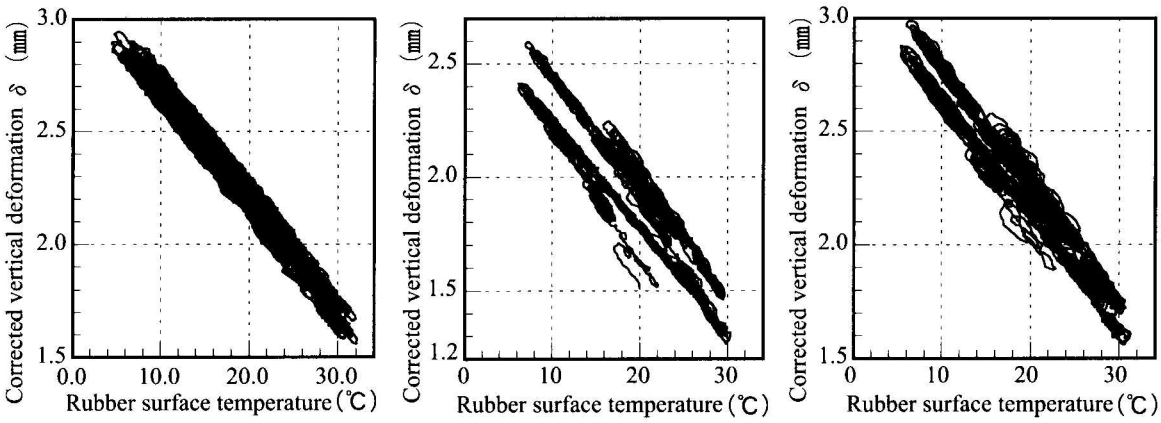


Figure 3 Changes in vertical deformation and air temperature(500X7-14, 445X4-25 specimen)



a) 500X3.75-26 specimen b) 500X7-14 specimen c) 445X4-25 specimen

Figure 4 Relationship between the rubber surface temperature and the vertical deformation corrected for the fluctuation of the compressive load

Table 3 Thermal coefficient $\alpha(mm/°C)$

		500×3.75-26	500×7-14	445×4-25
1 linear gradient		-0.0492296		
5 linear gradient	1 2357hours		-0.0549451	-0.0561798
	6143		-0.0467290	-0.0510204
	10990		-0.0561798	-0.0574713
	14848		-0.0490196	-0.0518135
	17300		-0.0564972	-0.0591716

Figures 6-9 show data obtained since the beginning of the creep test for 6:00 a.m., when there is little fluctuation in temperature. Here, creep is plotted over linear and logarithmic (semi-logarithmic) time axes. The figures use data from after the elapse of 2400 hours (100 days) to about 18,000 hours (about 2 years) to show estimation formulas using the least squares method. Table 4 lists values for creep for 50 and 100 years into the future estimated with these formulas. Due to differences in the formulas, there was as much as a 1000% differential in the estimated values. When the time axis was depicted as being linear, it was much severer in its evaluation than when the semi-logarithmic axis was used, yet even so it estimates that there would be only about 3mm creep under 200kg/cm^2 compressive stress during the next 100 years with specimen 500X3.75-26. Linear approximation provided the most critical evaluation. As seen in previous studies, creep apparently slows down after the passage of a certain number of years, but we will probably need to make observations over a much longer period to know if this is indeed true.

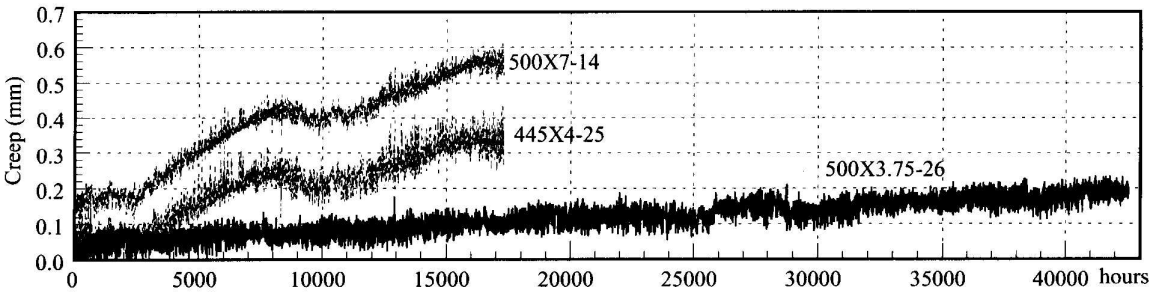


Figure 5 Changes of creep deformation

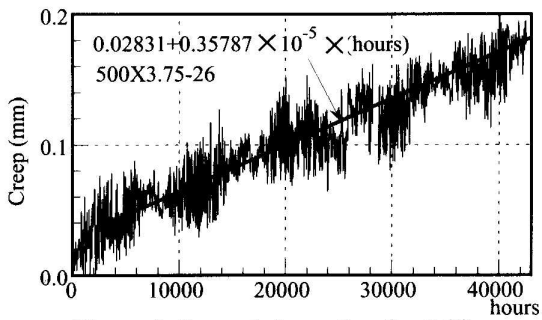


Figure 6 Creep deformation for 6:00a.m. (Linear time axis)

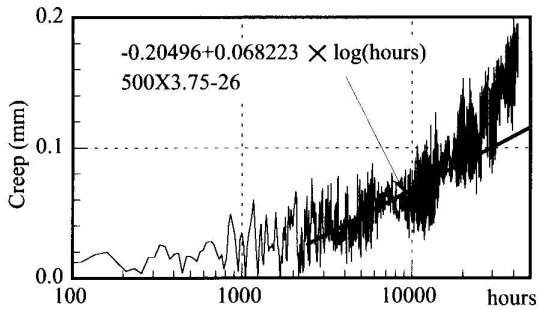


Figure 7 Creep deformation for 6:00a.m. (Semi-Logarithmic time axis)

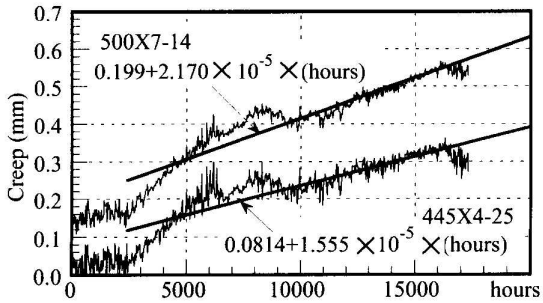


Figure 8 Creep deformation for 6:00a.m. (Linear time axis)

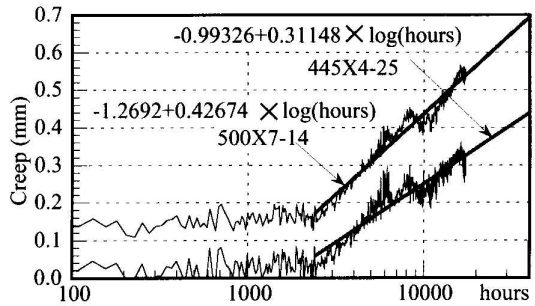


Figure 9 Creep deformation for 6:00a.m. (Semi-logarithmic time axis)

Table 4 Estimated creep value (mm)

Time axis	Specimen	50 years after	100years after
Linear axis (Linear)	500×3.75-26	1.60	3.19
	500×7-14	9.71	19.41
	445×4-25	6.89	13.78
Logarithm axis (Semilogarithm)	500×3.75-26	0.18	0.20
	500×7-14	1.14	1.27
	445×4-25	0.76	0.86

Figure 10 illustrates the relationship between the estimated creep rate (estimated creep / total thickness of rubber layers) for 50 and 100 years into the future, as derived by a linear approximation equation, and the primary shape factor S_1. The figure also shows a regression curve derived from the results of experiments conducted on specimens 500X3.75-26, 500X7-14 and 445X4-25 under the conditions of the secondary shape factor $S_2 \cong 5$ and axial stress of 100-200kg/cm^2. As S_1 increases, vertical stiffness becomes stronger, and the creep rate decreases. Figure 10 also depicts the estimated creep rate for the next 60 years based on the creep of laminated rubber bearing that was measured for about 10 years in various buildings with base isolation systems (references 5-7, with each reference notated in the figure). Table 5 provides an overview of the types of laminated rubber bearing used in these buildings. Observations of these buildings show values below the regression curve, especially as S_1 decreases. This is probably because the average axial stress used in these reports was about 50kg/cm^2, somewhat lower than the compressive stress used in the present study; at the same time, there were also differences in the observation periods and accuracy of estimation formulas. Nonetheless, just like the present study, the creep rate was lower in the specimens with higher S_1, regardless of the axial stress. This indicates that axial stress, within a certain range, has almost no relation with creep, which can be determined instead by S_1.

CONCLUSION

Using 3 types of laminated natural rubber bearings with a secondary shape factor $S_2 \cong 5$ and a different primary shape factor (S_1), creep tests were conducted for about 5 years and provided the following results:

1) It was apparent that creep values decreased as the primary shape factor S_1 increased. With specimen 500X3.75-26 of $S_1 \cong 33$, even the maximum estimated value for the creep rate after 100 years of use was only about 3%.
2) When axial stress was within a range of 100-200kg/cm^2, it showed almost no relationship with the creep rate, which instead tended to be dependent on S_1.
3) The effect of different physical properties of rubber on the state of creep, as well as the methods used for estimating future creep, should be further investigated.

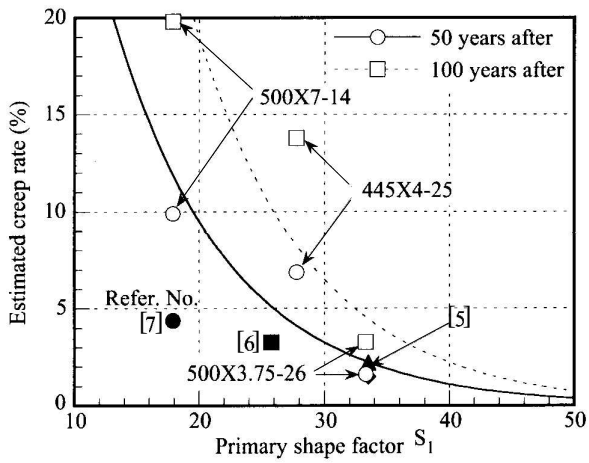


Figure 10 Relationship between the estimated creep rate and the primary shape factor

Table 5 Overview of the laminated rubber bearing used for real seismic isolated buildings

Refer. No.	Diameter	Rubber thickness	Number of layer	Center hole	S	S	Average axial stress	Observation period	Measuring method	Estimated creep	Approximation method
[5]	740mm	4.4mm	61	150mm	33.5	2.8	50 kg/cm^2	About 11 and half years	micrometer	5.88mm(2.2%)	Linear
								About 2 and half years	Laser displacement transducer	3.94mm(1.5%)	
[6]	670	6	23	50	25.8	4.86	56.5	About 10 years		4.5mm(3.3%)	Dual logarithms
[7]	500	7	14		17.9	5.1	45		Dial gauge	4.3mm(4.4%)	Linear

*Estimated creep value after 60 years ( ) inside a creep rate S_1:Primary shape factor S_2:Secondary shape factor

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