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THE TENSILE TESTS OF NATURAL RUBBER BEARINGS FOCUSED ON THE EFFECT OF THE STEEL FLANGE PLATES

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ABSTRACT

More than 800 base-isolated buildings have already been constructed in Japan, and the most of them use laminated rubber bearings. Recently, the application of the seismic isolation technology is spreading to very tall buildings. But when a strong earthquake attack the tall building with seismic isolation, there may happen that the columns at outside of the building are pulled up. Consequently, the research for the characteristics of laminated rubber bearings subjected to tensile load is now focused.

Therefore, in this study tensile tests are planned to investigate the effect of the thickness of flange plates on the mechanical characteristics and the scale effect.

1.INTRODUCTION

Recently, the application of base-isolation technology is spreading to high-rise buildings, and also to various shapes of the buildings. It is possible that tensile force acts on the laminated rubber bearings at outside of base-isolated buildings when a strong earthquake attacks them. Therefore, the research on the characteristics of laminated rubber bearings subjected to tensile load has been studied. But, neither testing methods for the tensile characteristics nor the shapes of specimens are standardized.

Therefore, the standardized tensile tests for laminated rubber bearings (Natural Rubber Bearing, High Damping Rubber bearing and Lead Rubber Bearing) with different rubber materials and shapes were carried out by the technical committee of Japan Society of Seismic Isolation (JSSI). [1] The purpose of these tests was to grasp the tensile property, the ultimate capacity, the change of basic characteristics and the breaking performance before and after each tension loading.

A laminated rubber bearing consists of the main body and flange plates: The main body is comprised of rubber sheets and steel plates (inner plates) bonded alternately and flange plates are needed to fix the bearing to the foundation and the upper building structure. The mechanical characteristics of the laminated rubber bearing depend on the primary shape factor S_1 and the secondary shape factor S_2. So, as a design rule, it is common that the values of S_1 and S_2 are fixed from small to large size of the isolator. But recently, it is found that the characteristics of laminated rubber bearings are influenced by not only S_1 and S_2 but also the specification of flange plate, inner plate and so on. [2][3] Especially, as for laminated rubber bearings subjected to tensile load, the influence of deformation of the flange plate would be important. But usually the specifications of the flange plates and inner plates are not perfectly proportional because of the limitation of the production. So it seems to be necessary to verify the effect of the thickness of flange plates on the mechanical characteristics as well as the scale effect.

In this report, as for Natural Rubber Bearing under tensile stress of about $-1N/mm^2$, we studied (1) Vertical/horizontal stiffness, (2) Scale effect of laminated rubber bearing, (3) Effect of the thickness of the flange plate. We made the following tests: (a) Tensile/compressive tests under constant offset shear strain, (b) Shear tests under constant tensile stress or strain. In these tests, flange plates of three different thickness were used to investigate the effect of the flange thickness. And rubber bearings of diameter 500mm and 1000mm were used to investigate the scale effect.

In this paper, the test results under small tensile deformation (tensile small deformation tests) are reported in addition to the results of the tensile tests under offset shear deformation (tensile large deformation tests) by JSSI. Besides, tensile stress level is expressed by negative (-).

2.SPECIMENS

Fig.1 shows the shape of a test specimen. The laminated rubber bearing is comprised of main body and flange plates. They are tied with bolts. The main body is comprised of rubber sheets, thin steel plates and two connecting steel plates at top and bottom bonded together. The shape of laminated rubber bearings is decided by the diameter D, the thickness of a rubber sheet t_R, and the numbers of the rubber sheets n. The primary shape factor is defined as S_1= (cross section /surface area of a rubber sheet)=D/4t_R, whereas the secondary shape factor S_2 is (diameter of a rubber sheet/total rubber thickness)=D/(n×t_R).

S_1 is an index which shows the effect of the restrain of the inner plate which brings large vertical stiffness and load capacity of the laminated rubber bearings, and the factor which influences the change of horizontal stiffness according to compressive stress. S_2 is the factor that influences the bend and the capacity of horizontal deformation of the laminated rubber bearings. All the specimens have no central holes, S_1 is 33, S_2 is 5.1, and they are proportional. The diameter of the inner steel plates is larger than the diameter of the rubber: so-called exposure type. The shear modulus G of rubber material is 0.44 N/mm^2.

The specification of test specimens in detail is described in Table 1. In tensile large deformation tests of JSSI the given tensile strain was up to 100%, specimen is 500mm in diameter of rubber and with the flange plates of 25mm thickness (Specification B).

In tensile small deformation tests under tensile pressure up to –1N/mm^2, specimens are 500mm in diameter of rubber and with three thickness of flange plates 20mm (Specification A), 25mm (B) and 36mm (C). The specimen of 1000mm in diameter of rubber is used to investigate the change of characteristics by the scale effect.

The thickness 36mm of the flange plates of 1000mm in diameter of rubber and the thickness 20mm of 500mm is almost proportional.

3.TESTING METHODS

3.1Testing apparatus

The experiments were accomplished by the use of a compressive/tensile-shear testing apparatus. The specification of testing apparatus is that the compressive load capacity is 15MN, horizontal load capacity is ±4MN and horizontal stroke is ±500mm.The horizontal load, vertical load, horizontal displacement were measured with load cells and displacement sensor of testing apparatus. Vertical displacement was measured with external displacement sensor close to the specimens.

3.2Test conditions

(1) Tensile large deformation test (tensile tests under offset shear deformation)

Under the constant shear deformation (offset shear), specimens were subjected to the tensile deformation. The cyclic tension of 10 times was subjected under 4 levels of offset shear strain: 0, 100, 200 and 300% of total rubber thickness. The tensile strain was set as 5, 10, 25, 50, 75 and 100% of 6 levels. The basic characteristics of vertical and horizontal stiffness were measured before and after each level of tensile deformation. Finally, the breaking or buckling characteristics was examined by the compressive shearing test for the specimens that experienced the tensile strain up to 100%.

The experimental research regarding the effect of tension for laminated rubber bearings was enforced by the technical committee of Japan Society of Seismic Isolation (JSSI). The device makers that cooperated to this experiment were 6 companies. The specimens used in this research were 7 types consisted of Natural Rubber Bearing, High Damping Rubber bearing and Lead Rubber Bearing. The diameter of specimens is about 500mm, the primary shape S_1 is about 30, and the secondary shape S_2 is about 5.

(2) Tensile small deformation tests

Tensile small deformation tests consist of (1) tensile and compressive test subjected to the loading from tensile to compressive continuously under the constant shear deformation, (2) shearing test under the constant tensile stress or strain and (3) simple tensile test. The procedure of tensile small deformation tests is shown in Table 2.The basic characteristics were checked between tensile tests in order to evaluate the change of vertical and horizontal stiffness before and after subjected to tensile load.

As for the tensile and compressive tests under the constant shear deformation, vertical load equal to －0.5⇔10 N/mm^2 and － 0.5 ⇔ 10 N/mm^2 stress were applied under the shear deformation set as 0,100 and 200% strain. As for shearing test under the constant tensile stress or strain, the horizontal deformation equal to ±100%, ±200% and ±250% shear strain were applied under the tensile stress set as 0, －0.5, －1.0 N/mm^2 of three stages and the tensile strain set as －10 and －25% of two stages. However, the specimen of 1000mm in diameter of rubber was not subjected to the horizontal deformation equal to ±250% strain.

As for simple tensile test, the tensile deformation equal to －50, －75 and －100% strain of three stages were applied. The cyclic deformation of 5 times was subjected in each tensile test.

The tests for the basic characteristics were carried out to evaluate the compressive stiffness under vertical load equal to 15N/mm^2±30% stress in design and the horizontal stiffness under vertical load equal to 15N/mm^2 stress in design with horizontal displacement equal to ±100, ±200 and ±250% strain. The cyclic deformation of 3 times was subjected in each test for the basic characteristics.

Moreover, the slit was installed in the testing apparatus to measure the deformation of the lower flange plate in each test. The measuring points are shown in Fig.2. Three sensors were arranged at the center, in the middle and at the end (close to the bolt) of the flange plate. The horizontal loading direction is shown as the arrow in Fig.2. The direction of the sensor array was rotated by 22.5 degrees from the loading direction in order to avoid the interference with fastening bolts.

3.3Evaluation of characteristic value

The method of evaluation of vertical stiffness and horizontal stiffness is shown in Fig.3.

The characteristic in each test was evaluated by effective stiffness using the maximum, the minimum load value, and the maximum, the minimum displacement value. However, the compressive stiffness in the tests for the basic characteristics was obtained using the load and displacement value under vertical load equal to design stress σ±30%.

The results of tensile small deformation tests for ϕ500mm and ϕ1000mm in diameter of rubber are converted to confirm the scale effect as follows.

The apparent tensile elastic modulus E_t and compressive elastic modulus E_c are defined by the tensile stiffness K_{vt} and the compressive stiffness K_{vc} as follows. The relation between horizontal stiffness K_h and the shear modulus G is defined as follows, too.

$$E=K_v \times h/A \quad (1)$$

$$G=K_h \times h/A \quad (2)$$

where h=total thickness of rubber and A=sectional area of rubber.

The vertical stress σ is obtained from dividing the vertical load P by the sectional area A of rubber and the vertical strain ε is obtained from dividing the vertical displacement Y by the total thickness h of rubber in compressive and tensile tests. The shear stress τ is obtained from dividing the vertical load Q by the sectional area A of rubber and the shear strain γ is obtained from dividing the horizontal displacement X by the total thickness h of rubber in compressive and tensile tests.

4.RESULT

4.1 Tensile large deformation test (tensile tests under offset shear deformation)

Fig.4 shows the specimen under tensile loading of 100% in tensile strain with shear strain of 200%. It shows that the central region of the specimen is constricted, because the inner plates generate the rotation by the increase of the bending deformation of rubber sheets. The strain distribution of upper and lower rubber layers is not uniform under the shear deformation.

Fig.5 shows the tensile stress-strain curves under constant shear strain 100%. The stress-strain curve is almost linear below tensile strain 10%. But when the strain exceeds 25%, the curves become to bend and show the characteristics like yield of materials. Fig.6 shows the tensile stress-strain curves under constant shear strain 0,100,200 and 300%. As the shear strain increases, the tensile yield stresses decrease and tend to increase the slope of the curves. Specimens did not break under the shear strain 0 to 200%, but it broke under the shear strain 300% and breaking tensile strain was 48%.

The results of this test and the results for Natural Rubber Bearing, High Damping Rubber bearing and Lead Rubber Bearing by the technical committee of Japan Society of Seismic Isolation (JSSI) are shown in Fig.7. The failure interaction curve is obtained by the results of all tensile tests and average breaking strain 400% in compressive shearing test. The performance of tensile deformation is seemed to be larger than the curve from these results.

The results of tests for the basic characteristics before and after each level of tension deformation are shown in Fig.8. With increasing tensile deformation from 5% to 100% in strain, the change of compressive stiffness and horizontal stiffness is small before and after the tests.

Finally Fig. 9 shows the shear stress-strain curve of the ultimate shear deformation of the specimen under 10N/mm^2 compressive stress, which had been subjected to the 100% tensile strain under 0% of shear strain. The shear strain at break is 427%, which is larger then the average of initial break strain. This seems to mean the ultimate shear deformation capacity under usual compressive load is maintained after the experience of tensile deformation.

4.2 Tensile small deformation tests

(1) Offset tensile/compressive test

Test result for the specimen of rubber diameter 500mm and flange plate 20mm is shown in Fig. 10. That shows the vertical stress-strain curves for load pressure 10~–1.0N/mm^2 under 0, 100 and 200% of offset shear strain. It can be understood that the tensile stiffness as well as the compressive stiffness reduces as the offset shear strain increases.

Fig .11 shows the vertical stress-strain curves for simple tensile compressive test of 500mm specimen with flange plate thickness 20mm and 36mm. That shows the tensile characteristic strongly depends on the flange plate thickness.

Fig. 12 and Fig. 13 show the plot of the tensile stiffness (modulus dimension) of 500mm specimens to the offset shear strain for three flange plate thickness. The thicker the flange plate is, the higher the tensile stiffness is. But the difference of 20mm and 25mm is small. The tensile stiffness of the specimen of 36mm flange is more than twice of that of 20mm flange at the vertical stress –0.5N/mm^2, but the difference is smaller at the vertical stress –1.0N/mm^2. This phenomenon can be understood that the tensile stiffness reduced at –1.0N/mm^2 because the tensile yield of the rubber got dominant as shown in Fig. 14.

Fig. 15 shows the vertical stress-strain curves at offset shear strain of 200% for 500mm and 1000mm specimens. They are almost similar. Further Fig. 16 shows the plot of the tensile stiffness (modulus dimension) to the offset shear strain for 500mm and 1000mm specimen. The tensile stiffness of the 1000mm specimen is a little lower than that of the 500mm specimen. The difference seems to come from the fact that the details of the flange plates and laminated steel plates are not perfectly proportional.

(2) Shear test under constant tensile condition

Fig. 17 shows the shear stress-strain curves of the 500mm specimen with 20mm flange plate for ±250% shear strain, under the vertical stress of 15, 0, –0.5 and –1.0N/mm^2. The area of the hysteresis loop under the vertical stress of 0~–1.0N/mm^2 is a little smaller then that of 15N/mm^2. And the shape of the loop for –1.0N/mm^2 is more linear than other loops. The shear stress-strain curves of the 500mm specimen with 20mm flange plate for ±250% shear strain, under the tensile strain of 10 and 25% are almost similar to that of –0.5 and –1.0N/mm^2.

Fig. 18 and Fig.19 show the shear stress-shear strain curves and vertical strain-shear strain curves respectively of the 500mm specimens with 20mm and 36mm flange plates for ±250% shear strain, under the load pressure of –1.0N/mm^2. The curves for two flange plate thickness show good coincidence in both figures. Fig. 20 shows the dependency of the shear stiffness (modulus dimension) on shear strain of 500mm specimens, for flange plate thickness of 20mm and 36mm. From the result, it can be understood that the shear stiffness is not affected by the flange plate thickness.

The dependency of the shear stiffness on shear strain under constant tensile strain of 10% and 25% are similar to that under the constant load pressure of –0.5 and –1.0N/mm^2 respectively. Especially because the tensile load pressure of –1.0N/mm^2 corresponds to tensile strain of 25%, shear stiffness for them is almost the same.

Fig. 21 and Fig.22 show the shear stress-shear strain curves and vertical strain-shear strain curves respectively of the 500mm and 1000mm specimens of scale model for ±250% shear strain, under the load pressure of –1.0N/mm^2. The shear stress-shear strain curves are almost similar, but vertical strain-shear strain curves are a little different. Fig. 23 shows the dependency of the shear stiffness on shear strain under load pressure of 15, 0, –0.5 and –1.0N/mm^2. The result is the same tendency as Fig. 21. Consequently as for the shear stiffness, the scale effect is small.

(3) Simple tensile test

Fig. 24 shows the 1st cycle loop and 5th cycle loop of the simple tensile tests of 500mm specimens with 20mm and 36mm flange plates. In small deformation, there is a little difference of the loops with respect to the flange plate thickness, but in large deformation there are no difference. This means, in large tensile deformation, the deformation of the rubber becomes dominant, in the other hand the deformation of the flange plate is relatively small.

Fig. 25 shows the 1st cycle loop and 5th cycle loop of the simple tensile tests of 500mm and 1000mm specimens. There is a little difference of the loops with respect to the size. That may come from the fact that 500mm and 1000mm specimens are not perfectly proportional in the details.

Assuming the flange plate to be a simple circular plate, which is simply supported at periphery, with uniformly distributed load p, the deflection of the flange plate is given as equation (3) and equation (4).

When $0 \le r \le b$

$$d = \frac{pb^4}{16D}\left[\frac{r^4}{4b^4} - \frac{4a^2-(1-\nu)b^2}{2(1+\nu)a^2}\left(\frac{r}{b}\right)^2 - \left(2\frac{r^2}{b^2}+1\right)\ln\frac{b}{a} + \frac{4(3+\nu)a^2-(7+3\nu)b^2}{4(1+\nu)b^2}\right] \qquad (3)$$

When $b \le r \le a$

$$d = \frac{pb^4}{16D}\left[\frac{1}{2(1+\nu)}\left(1-\frac{r^2}{a^2}\right)\left\{2(3+\nu)\frac{a^2}{b^2}-(1-\nu)\right\} - \left(1+\frac{2r^2}{b^2}\right)\ln\frac{a}{r}\right] \qquad (4)$$

where $D=Eh^3/\{12(1-\nu^2)\}$, E: Young’s modulus, ν:Poisson ratio, h: plate thickness, a: distance from the center to the fastening bolts, b: radius of connecting plate.

Fig. 26 shows the calculated values (shown as the lines) and measured values of the flange deflection with respect to the radial distance from the center. Theoretical values are much greater than measured ones. Then, by converting the thickness of the connecting plate to equivalent thickness of the flange plate, the additional flange thickness Δt is calculated as equation (5).

$$\Delta t = \left(\frac{D_r}{D_{fp}}\right)^2 t_r' \qquad (5)$$

where D_r: diameter of connecting plate, D_{fp}: PCD of fastening bolts. t_r’ of 500mm specimen and 1000mm specimen are 12mm and 20mm respectively.

Fig. 27 shows the modified calculated values using equation (3). That shows good correspondence to measurement result. From these results, it seems possible that flange deflection is evaluated by using the equivalent flange thickness and scale rule is applicable.

5.CONCLUSION

From above study, we conclude as for the tensile behavior of Natural Rubber Bearing:

(1) The tensile failure interaction curve was derived from tensile large deformation test. It became clear that the laminated rubber bearing has large capability of tensile deformation.

(2) The basic characteristics (compressive and shear stiffness) and ultimate shear deformation capacity are maintained even after the tensile experience.

(3) The tensile stiffness is sensitive to the flange plate thickness, from the result of offset tensile/compressive test.

(4) It became clear from the tensile shear test that the shear stiffness was not influenced by neither the tensile condition nor flange plate thickness, even the vertical tensile deformation increased during the shear test under –1.0N/mm^2 of tensile stress (corresponding to 10~20% of tensile strain).

(5) The scale effect in small tensile region is small, from the tests of 500mm and 1000mm specimens.
(6) It is possible to reduce the tensile deformation of the rubber part by making the flange thickness thin. But it is necessary to study the local strain or stress in detail.
(7) The deflection of the flange plate is evaluated with the simple formula by considering the equivalent flange plate thickness.

As the next theme, we would like to propose the design rules of the flange plate for laminated rubber bearings under tensile condition, by studying the detailed model with FEM analysis etc.

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[3]Yoshitake M, Ichiro N, Ichizou K, Masaharu T, Yuichi K, 2001, "Tensile Property of Large-sized Natural Rubber Bearing", Journal of Technology and Design (AIJ), No.12, pp53-56.

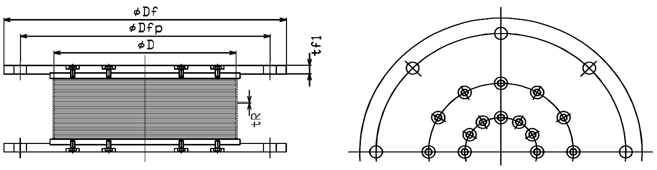
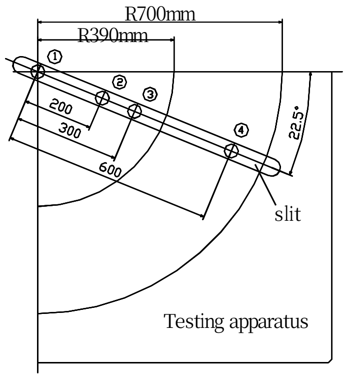


Figure1: The shape of a test specimen



R700mm : Radius of flange plate for φ1000 specimen
[mesuring point ①,②,③]
R390mm : Radius of flange plate for φ500 specimen
[mesuring point ①,③,④]

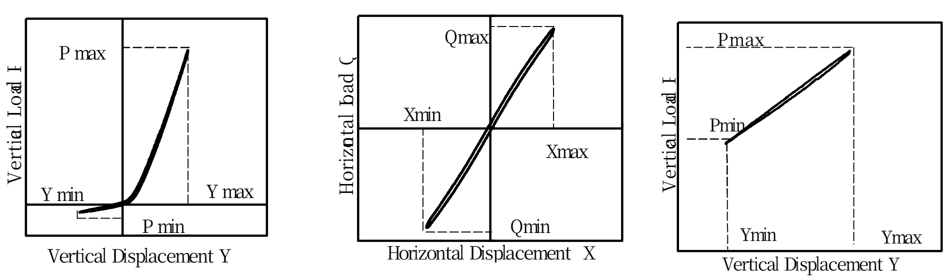
Figure2: Measuring points of deflection of a flange plate

Table1: Specification of test specimens

	Specification of laminated rubber bearing	NB45-500			NB45-1000
		A	B	C	
1	Shear modulus : G (N/mm^2)	0.44			0.44
2	Diameter of a rubber sheet : D (mm)	500			1000
3	Thickness of a rubber sheet : t_R (mm)	3.75			7.5
4	Number of rubber sheets : n	26			26
5	Total thickness : L [=n×t_R] (mm)	97.5			195
6	Primary shape factor : S_1	33.3			33.3
7	Secondary shape factor : S_2	5.1			5.1
8	Diameter of a flange plate : D_f (mm)	780			1400
9	Thickness of a flange plate : t_{f1} (mm)	20	25	36	36
10	Bolt hole P.C.D. of a flange plate Dfp (mm)	690			1265

Table 2: Procedure of tensile small deformation tests

Initial (basic) characeteristics test
Evaluation of vertical and horizontal stiffness under compressive stress in design
⇩
Offset tensile/compressive test
Evaluation of vertical stiffness for tensile and compressive loading under constant shear strain
Shearing test under constant tensile deformation
Evaluation of horizontal stiffness under constant tensile stress or strain
⇩
Basic characeteristics test 1
Evaluation of vertical and horizontal stiffness under compressive stress in design after small tensile deformation
⇩
Simple tensile test
Evaluation of vertical characteristics for large tensile deformation
⇩
Basic characeteristics test 2
Evaluation of vertical and horizontal stiffness under compressive stress in design after large tensile deformation



(a)Compressive stiffness Kc=Pmax/Ymax
(b)Tensile stiffness Kt=Pmin/Ymin

Horizontal stiffness
Kh=(Qmax-Qmin)/(Xmax-Xmin)

Vertical stiffness
Kv=(Pmax-Pmin)/(Ymax-Ymin)

Figure3: Evaluation of vertical and horizontal stiffness

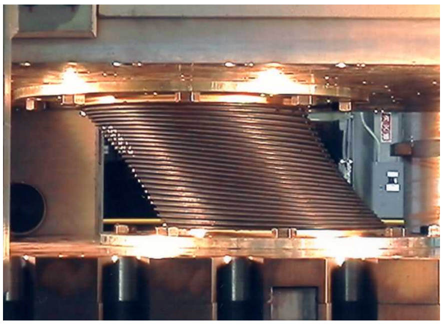


Figure4: Specimen under tensile loading of 100% in tensile strain with shear strain of 200%.

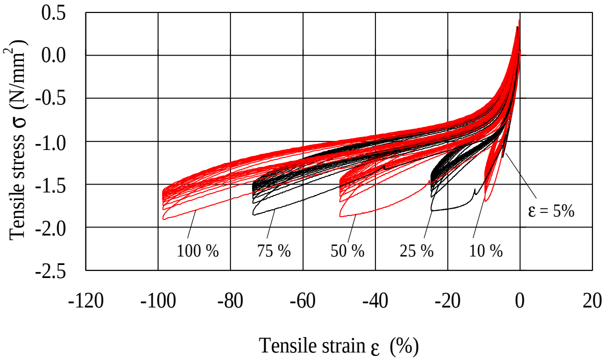


Figure5: Tensile stress-strain curves under constant shear strain 100%.

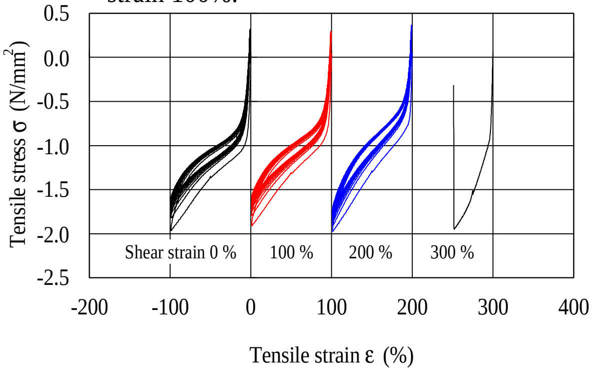


Figure6: Tensile stress-strain curves under constant shear strain 0,100,200 and 300%.

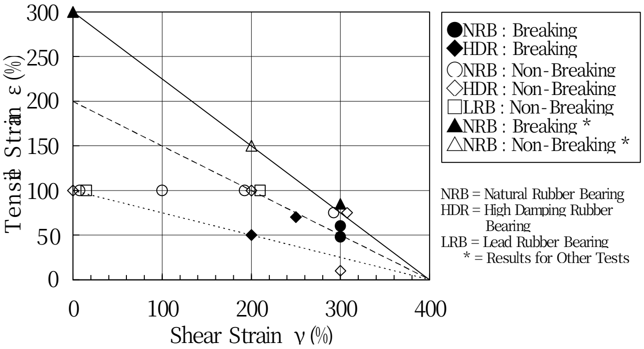


Figure7: Results of tests by JSSI

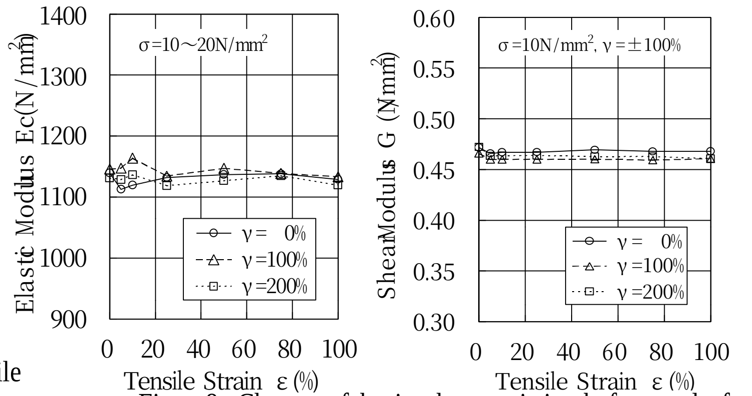


Figure8: Change of basic characteristics before and after tensile loading.

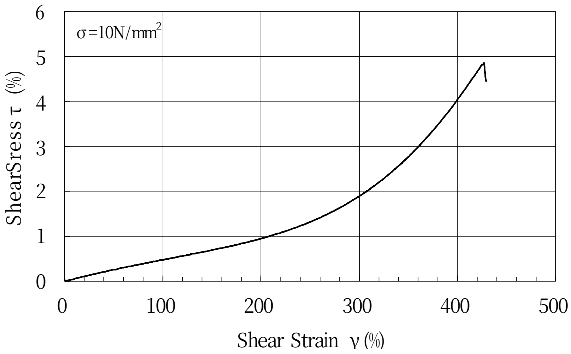


Figure9: Breaking characteristic after tensile loading

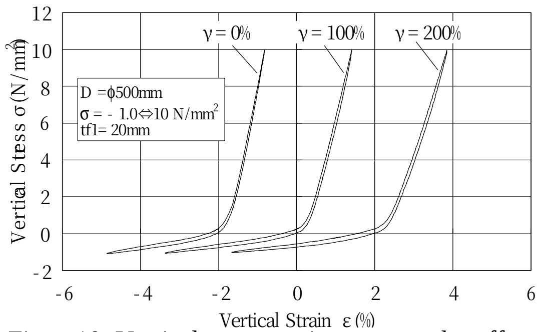


Figure10: Vertical stress-strain curves under offset shear strain

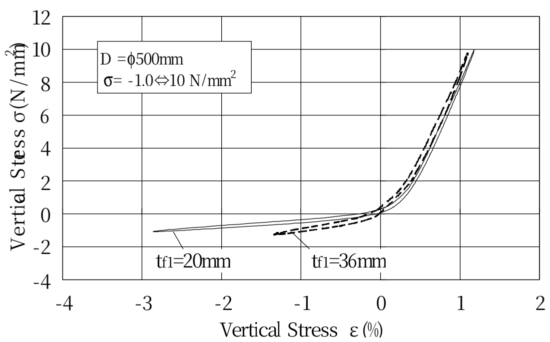


Figure11: Vertical stress-strain curves with different flange plate thickness

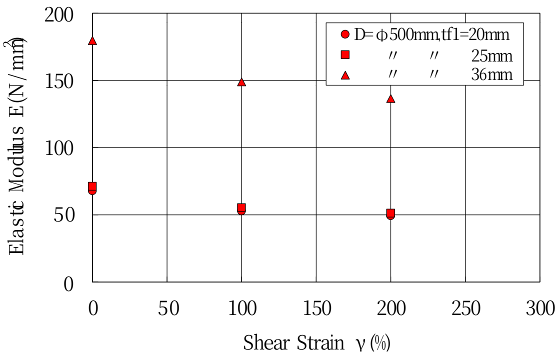


Figure12: Tensile stiffness under vertical stress –0.5N/mm^2

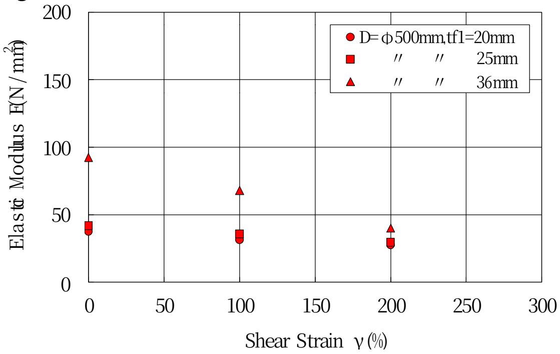
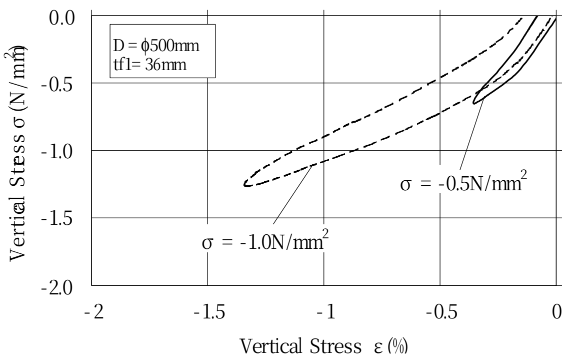


Figure13: Tensile stiffness under vertical stress –1.0N/mm^2



Firure14: Relation between vertical stress and stress-strain curves

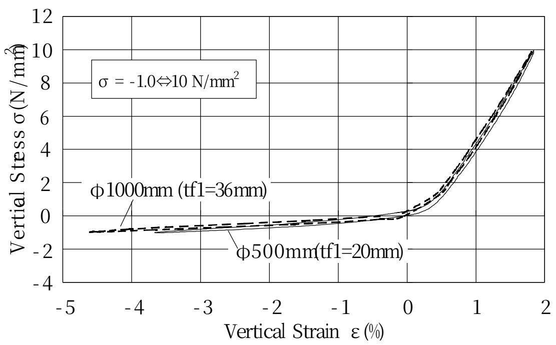


Figure15: Vertical stress-strain curves for scale effect

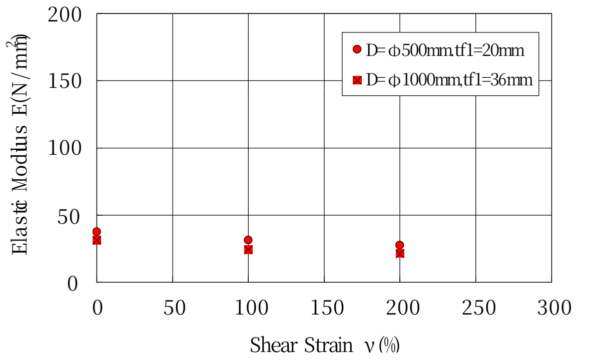


Figure16: Relation between tensile stiffness and scale effect

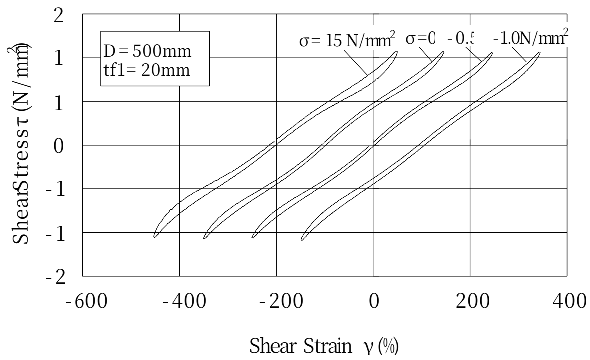


Figure17: Shear stress-strain curves under constant vertical stress

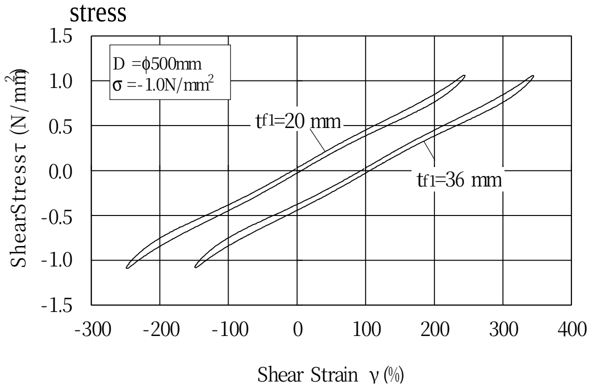


Figure18: Horizontal stress-strain curves with different flange plate thickness

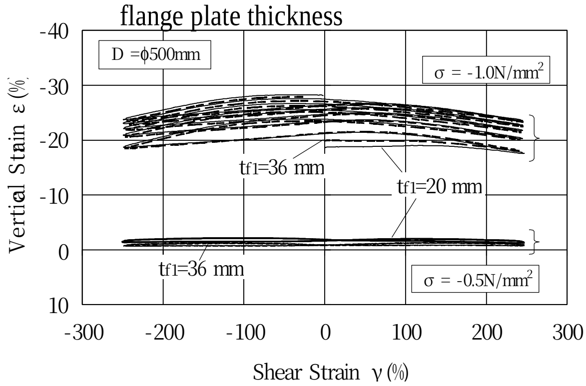


Figure19: Vertical strain-shear strain curves with different flange plate thickness

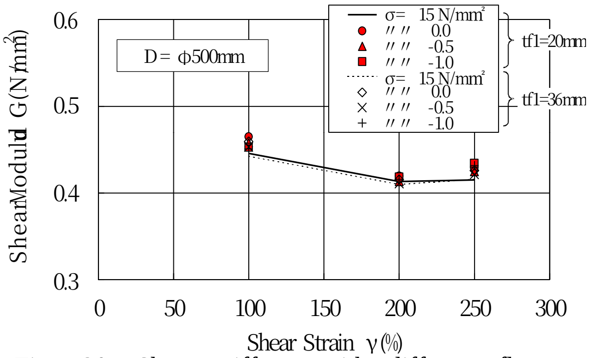


Figure20: Shear stiffness with different flange plate thickness

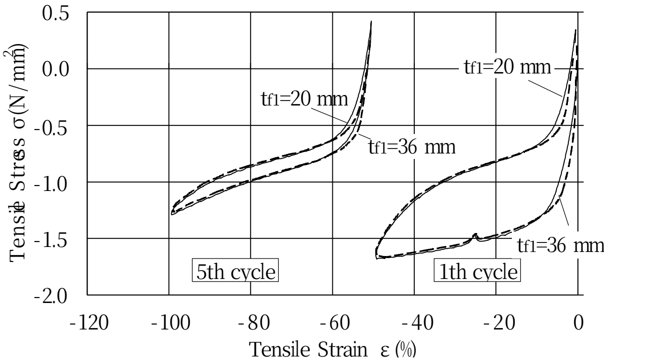


Figure24: Large tensile characteristics with different flange plate thickness

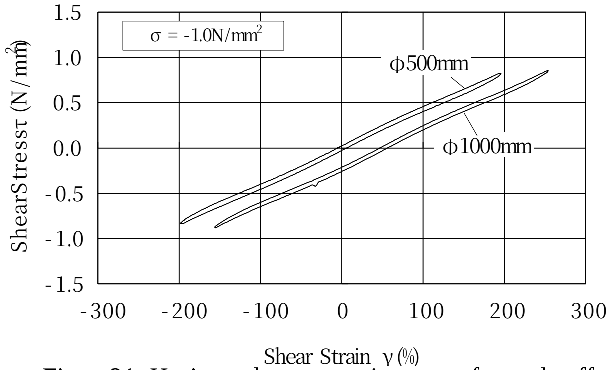


Figure21: Horizontal stress-strain curves for scale effect

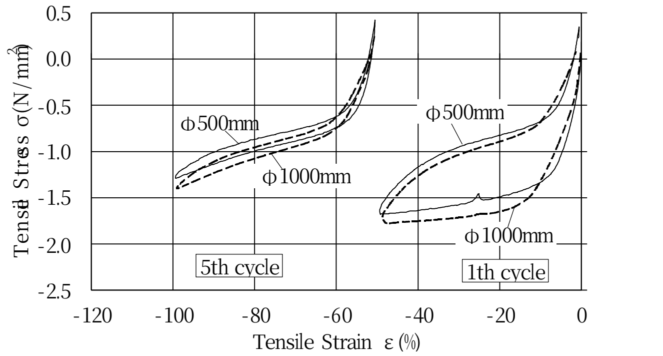


Figure25: Large tensile characteristics for scale effect

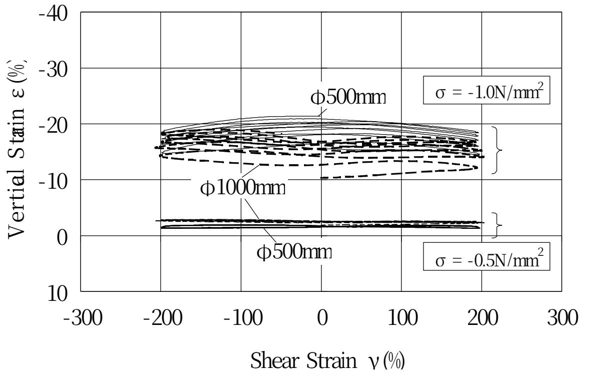


Figure22:Vertical strain -shear strain curves for scale effect

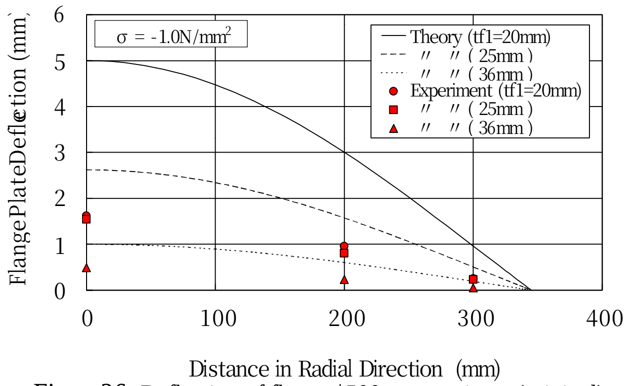


Figure26: Deflection of flange ϕ500mm specimen (original)

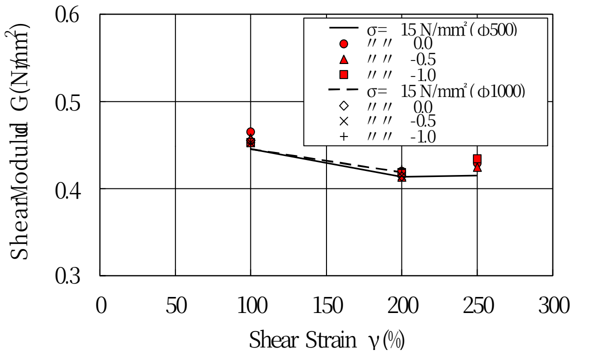


Figure23: Relation between Shear stiffness and scale effect

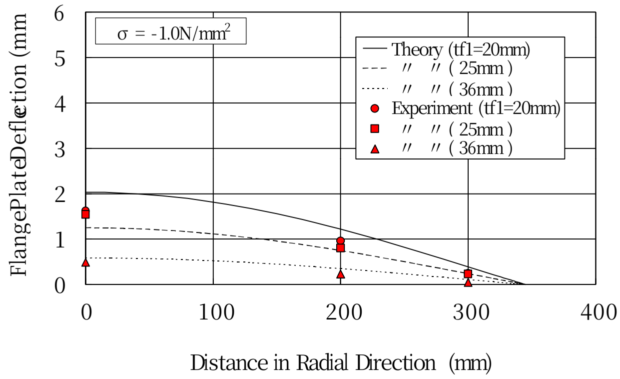


Figure27: Deflection of flange ϕ500mm specimen (modified)