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

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SUMMARY

This paper presents the experimental results from the tensile loading of laminated rubber bearings that are used for the base-isolated buildings. The tensile tests are carried out to understand the mechanical characteristics of Natural Rubber Bearings (NRB) under tensile stress up to -1N/mm^2 as the usual design limit. The vertical and horizontal characteristics are investigated as to the effect of flange plate thickness and the scale effect. These characteristics are evaluated by the tensile-compressive tests under constant shear strain and the shear tests under constant tensile stress or strain. For the effect of flange plate thickness, the flanges with different thickness are used for 500mm in diameter of NRB. For the scale effect, NRB with a diameter of 500mm and 1000mm of the same shape factors are used. From the tests results, it is found that the tensile stiffness is sensitive to the flange plate thickness, the shear stiffness under tensile stress -1N/mm^2 is not influenced by neither the tensile condition nor flange plate thickness and the scale effect in small tensile region is small.

1. INTRODUCTION

Recently, the application of the base-isolated system using laminated rubber bearings is spreading to very tall buildings and also to various shapes of the buildings. But when a strong earthquake hits the tall base-isolated building, there may happen that the columns at outside of the building are pulled up and the tensile load may act on the laminated rubber bearings. Consequently, the research for the characteristics of laminated rubber bearings subjected to tensile load is now focused. 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) (Iwabe [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.

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The laminated rubber bearings are consisted of the part of rubber and flange plates: The part of rubber is vulcanized and bonded between rubber layers and thin steel plates (inner plates) alternately and flange plates are needed to fix to the foundation and the building. 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 laminated rubber bearing. 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 (Hamaguchi [2], Muramatsu [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.

Therefore, in this study tensile tests were planned to carry out to investigate the effect of the thickness of flange plates on the mechanical characteristics and the scale effect. The specimen is Natural Rubber Bearings (NRB) and it is considered that test condition is tensile stress up to -1N/mm^2 that is the usual design limit of base-isolated buildings. In this paper, the tests for NRB were performed to investigate (1) Vertical/horizontal characteristics, (2) Scale effect and (3) Effect of the thickness of the flange plate under tensile stress 1N/mm^2. These characteristics are evaluated by (a) Tensile-compressive tests under constant offset shear strain and (b) Shear tests under constant tensile stress or strain. For the effect of flange plate thickness, the specimens with the different flange plates are tested for 500mm in diameter of specimens. For the scale effect, specimens with a diameter of 500mm and 1000mm of the same shape factors are tested. 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 consists of main body and flange plates. They are tied with bolts. The main body is comprised of rubber layers, thin steel plates (inner 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 layer t_R, and the numbers of the rubber layers n. The primary shape factor is defined as S_1 = (cross section /surface area of a rubber layer)=$D/4t_R$, whereas the secondary shape factor S_2 = (diameter of a rubber layer/total rubber thickness)=$D/(n\times t_R)$. S_1 is an index which shows the effect of the restrain of the inner plates 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 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 by 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 stress 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.

Table1 Specification of test specimens

Specification of NRB		NB45-500			NB45-1000
		A	B	C	
1	Shear modulus G(N/mm^2)	0.44			0.44
2	Diameter of a rubber layer D(mm)	500			1000
3	Thickness of a rubber layer t_R(mm)	3.75			7.5
4	Number or rubber sheets n	26			26
5	Total rubber thickness L [=n*t_R](mm)	97.5			195.0
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 D_{fp}(mm)	690			1265

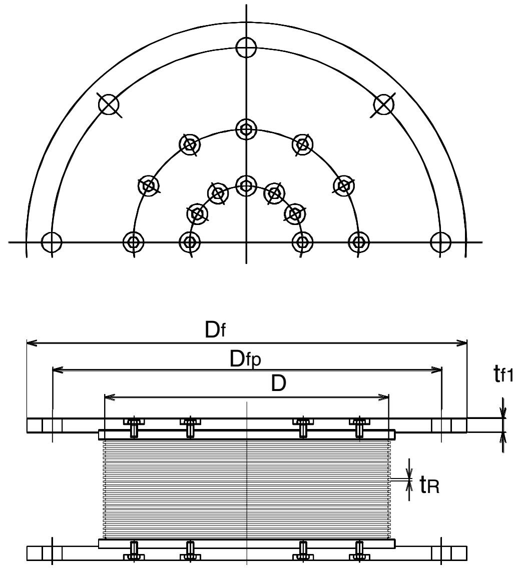


Fig.1 Shape of a test specimen

3.TESTING METHODS

3.1 Testing 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.

3.2 Test conditions

(1) Tensile large deformation tests (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 specimen 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.

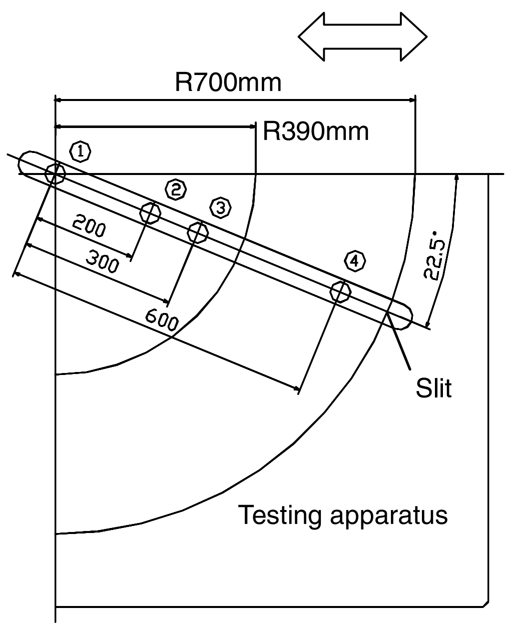
(2) Tensile small deformation tests

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) shear test under the constant tensile stress or strain and (3) simple tensile test. The procedure of tensile small deformation tests is summarized in Table 2. The basic characteristics were checked between tensile tests in order to observe 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 –1.0 ~ 10 N/mm^2 stress were applied under the shear deformation set as 0, 100 and 200% in strain. As for shear test under the constant tensile stress or strain, the horizontal deformation equal to ±100%, ±200% and ±250% in shear strain were applied under the tensile stress set as 0, –0.5, –1.0 N/mm^2 of three levels and the tensile strain set as –10 and –25% of two levels. However, the specimen of 1000mm in diameter of rubber was not subjected to the horizontal deformation equal to ±250% in strain. As for simple tensile test, the tensile deformation equal to –50, –75 and –100% in strain of three levels 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% in stress and the horizontal stiffness under vertical load equal to 15N/mm^2 in stress with horizontal displacement equal to ±100, ±200 and ±250% in strain. The cyclic deformation of 3 times was subjected in each test. Moreover, the slit was installed in the testing apparatus to measure the deflection 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.

Table2 Procedure of tensile tests

Initial basic characteristics test
Evaluation of vertical and horizontal stiffness under compressive stress
↓
Offset tensile-compressive test [Tensile test A]
Evaluation of vertical stiffness for tensile and compressive loading under constant shear strain
Shear test under constant tensile deformation
Evaluation of horizontal stiffness under constant tensile stress or strain
↓
Basic characteristics test 1
Evaluation of vertical and horizontal stiffness under compressive stress after small tensile deformation
↓
Simple tensile test [Tensile test B]
Evaluation of vertical characteristics for large tensile deformation
↓
Basic characteristics test 2
Evaluation of vertical and horizontal stiffness under compressive stress after large tensile deformation



R700mm: Radius of flange plate for D=1000mm
[Measuring point No.1, 3, 4]
R390mm: Radius of flange plate for D=500mm
[Measuring point No.1, 2, 3]

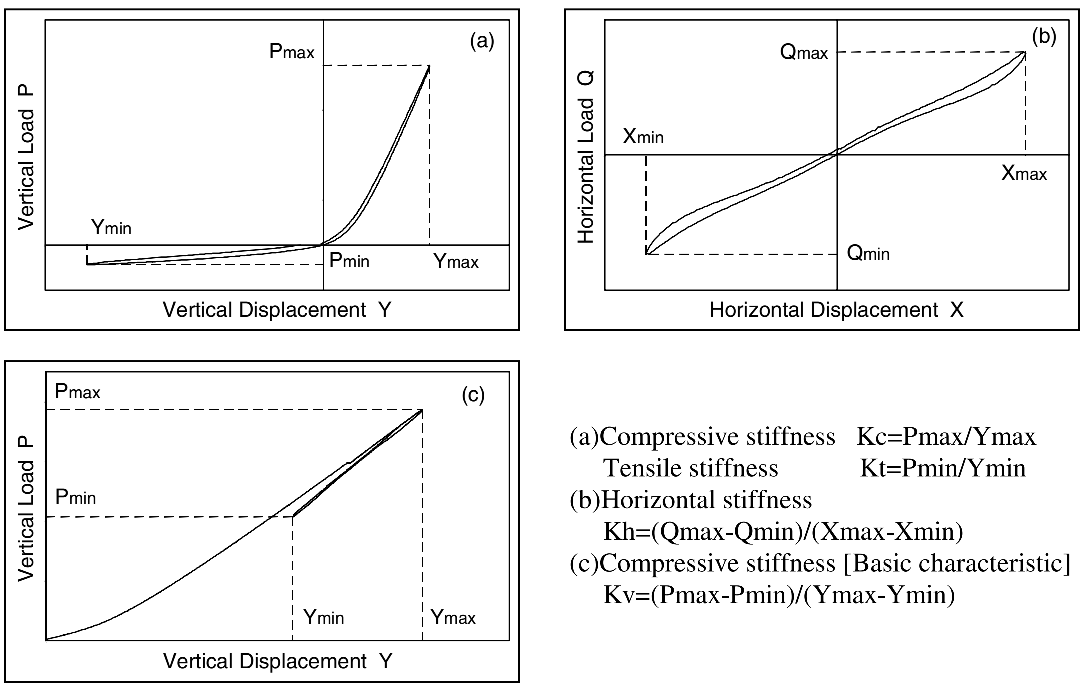
Fig.2 Measuring points of deflection

3.3 Evaluation of vertical and horizontal characteristics

The method of evaluation of vertical stiffness and horizontal stiffness is shown in Fig. 3. The characteristics in each test were 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 stress of σ ±30%. The results of tensile small deformation tests for 500mm and 1000mm 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 as Eq.(1) with the tensile stiffness K_{vt} and the compressive stiffness K_{vc}. The relation between horizontal stiffness K_h and the shear modulus G is defined as Eq.(2).

$$E = K_v \times h/A \tag{1}$$
$$G = K_h \times h/A \tag{2}$$

where h=total thickness of all rubber layers 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. The shear stress τ is obtained from dividing the horizontal 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 all rubber layers.



(a)Compressive stiffness Kc=Pmax/Ymax
Tensile stiffness Kt=Pmin/Ymin
(b)Horizontal stiffness
Kh=(Qmax-Qmin)/(Xmax-Xmin)
(c)Compressive stiffness [Basic characteristic]
Kv=(Pmax-Pmin)/(Ymax-Ymin)

Fig.3 Evaluation of vertical and horizontal stiffness

4.RESULT

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

Fig. 4 shows the specimen under tensile strain of 100% 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 layers. 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 of 100%. The stress-strain curve is almost linear below tensile strain of 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 of 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 of 0, 100 and 200%, but it broke under the shear strain of 300% and breaking tensile strain was 48%. The results of these test and the tests for Natural Rubber Bearing, High Damping Rubber bearing and Lead Rubber Bearing by the technical committee of Japan Society of Seismic Isolation (JSSI) as a function of shear strain are shown in Fig. 7. The failure interaction curve is obtained by the results of all tensile tests and average breaking strain of 400% in compressive shearing test. It became clear that the laminated rubber bearing has large capability for tensile deformation. 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 tensile tests. Finally, Fig. 9 shows the shear stress-strain curve for breaking test under 10N/mm^2 in compressive stress for the specimen that had been subjected to the 100% in tensile strain under 0% in shear strain. The shear strain at break is 427%, which is larger than 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.

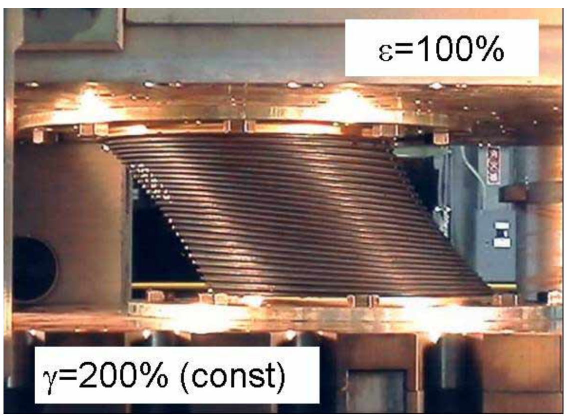


Fig.4 NRB under tensile deformation

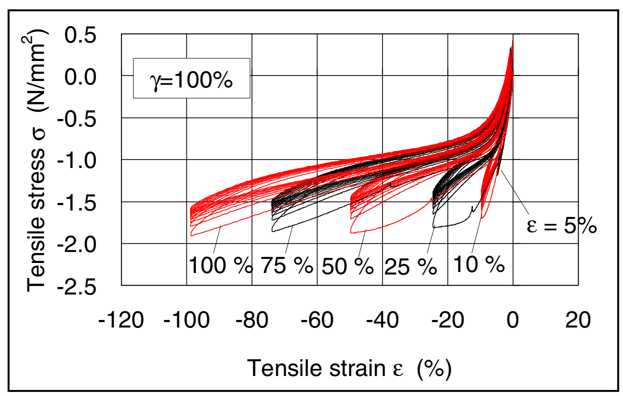


Fig.5 Tensile stress-strain curve

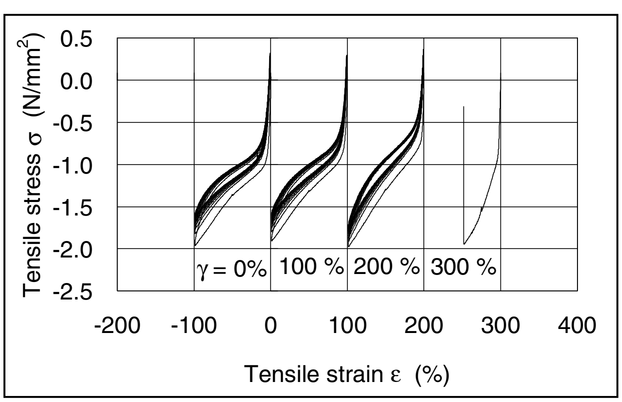


Fig.6 Tensile stress-strain curve

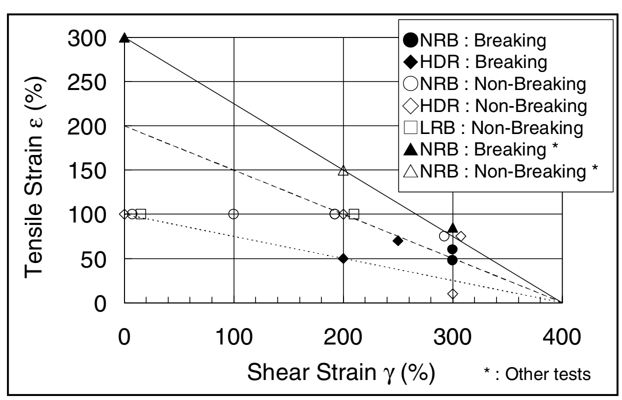
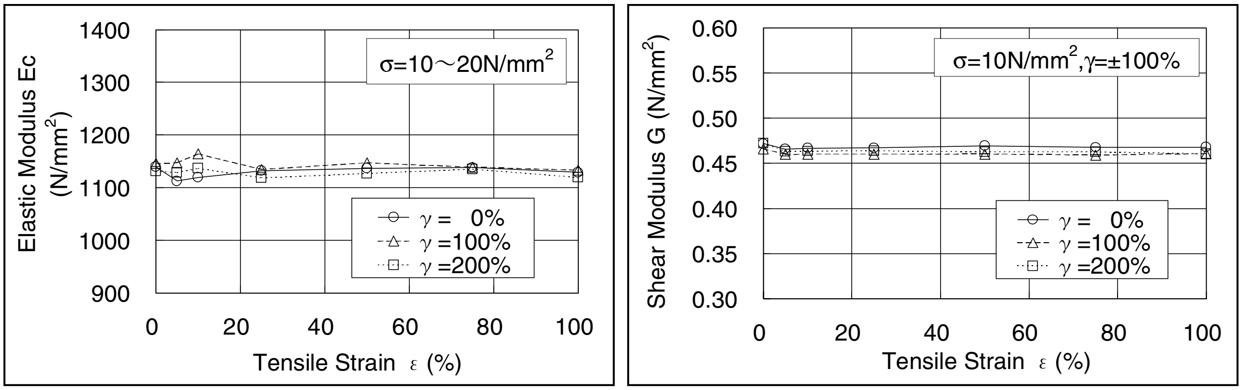


Fig.7 Results of tensile tests by JSSI



(a)Compressive stiffness **(b)Horizontal stiffness**

Fig.8 Basic characteristics before and after tensile test

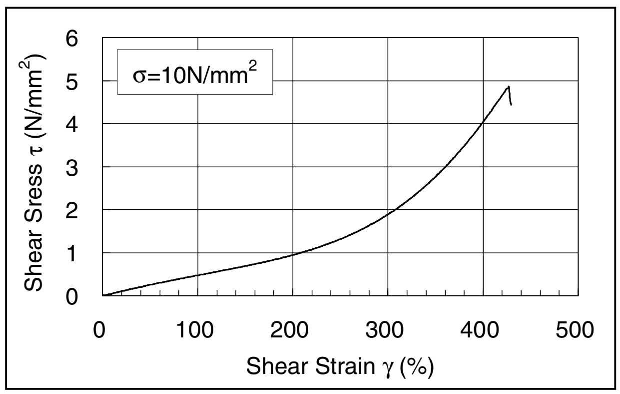


Fig.9 Breaking characteristic after tensile test

4.2 Tensile small deformation tests

First the deviation of the basic characteristics of the specimens is checked. The results of the initial basic characteristics are shown in Table 3. The deviation of the vertical and horizontal stiffness of all specimens is very small. Especially, the difference between the design value and measured value of the horizontal stiffness is about 1% under γ=±100% in shear strain.

Table3 Initial basic characteristics

D (mm)	T_{f1} (mm)	Ec (N/mm^2)	G (N/mm^2)		
			γ=±100%	γ=±200%	γ=±250%
500	20	1254	0.446	0.413	0.419
	25	1268	0.443	0.409	0.415
	36	1215	0.443	0.410	0.416
1000	36	1213	0.445	0.419	0.423

(1) Offset tensile-compressive test

The results of offset tensile-compressive tests for the specimen of rubber diameter 500mm with the flange plate thickness 20mm is shown in Fig. 10. That shows the vertical stress-strain curves for vertical stress of 10 ~ –1.0N/mm^2 under 0, 100 and 200% in 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 for 500mm specimen with the 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 tensile stiffness (elastic modulus *E*) of 500mm specimens with the three different flange plates as a function of shear strain. The thicker the flange plate is, the higher the tensile stiffness is. But the difference of the flange plate thickness 20mm and 25mm is small. The tensile stiffness of the specimen with the flange plate thickness 36mm is more than twice of that with the flange plate thickness 20mm under the vertical stress of –0.5N/mm^2, but the difference is smaller under the vertical stress of –1.0N/mm^2. This phenomenon can be understood that the tensile stiffness reduced under –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 200% for 500mm and 1000mm specimens. They are almost similar. Further Fig. 16 shows the tensile stiffness for 500mm and 1000mm specimen as a function of shear strain. 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 inner plates are not perfectly proportional. The relation between the number of times of a repetition and the tensile stiffness is shown for 500mm specimens with different flange plates in Fig.17. The change of tensile stiffness of two different specimens is very small under tensile stress of –0.5N/mm^2. The tensile stiffness of the specimens with the flange plate thickness 36mm decreases remarkably in comparison with that of the flange plate thickness 20mm under tensile stress of –1.0N/mm^2. The reason is that the deformation of the part of rubber is dominant by the thick flange plate. So, it seems that if the thickness of the flange plate is decided properly, the repeated deformation dependence will reduce.

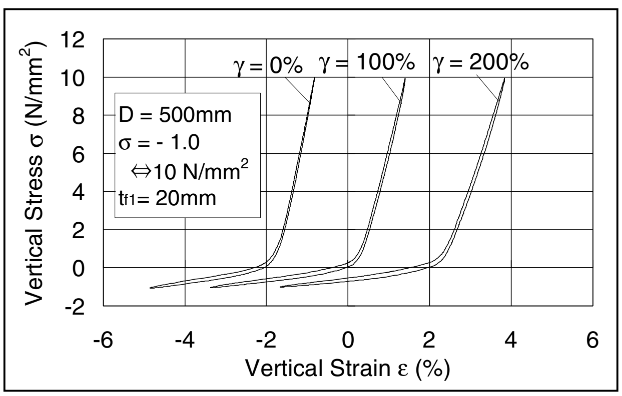


Fig.10 Vertical stress-strain curves

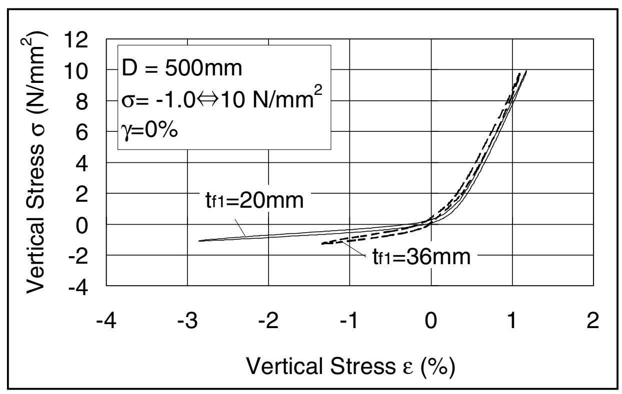


Fig.11 Vertical stress-strain curves

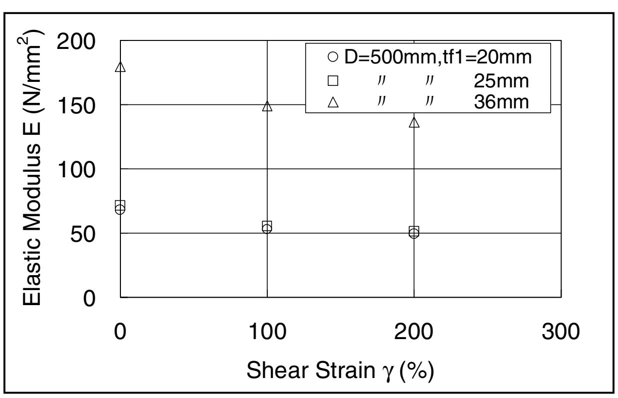


Fig.12 Tensile stiffness under σ=-0.5N/mm^2

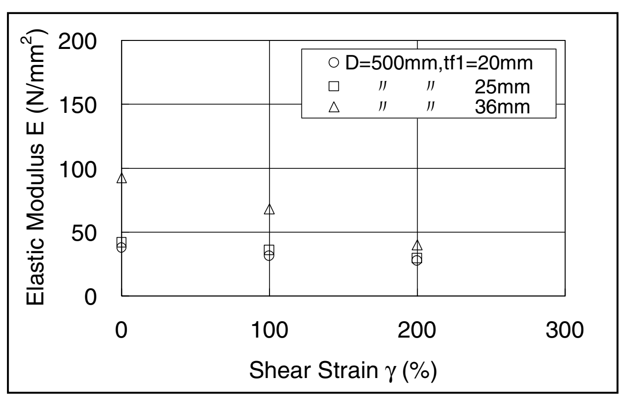


Fig.13 Tensile stiffness under σ=-1.0 N/mm^2

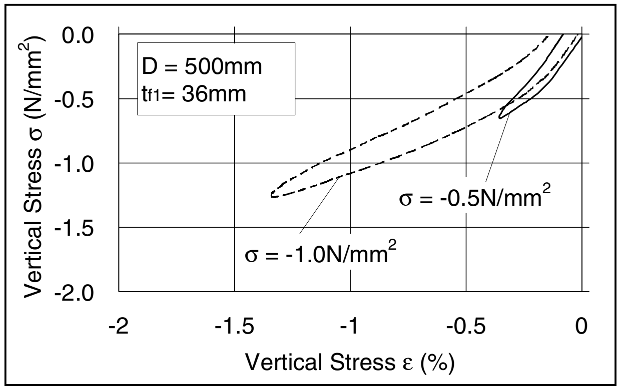


Fig.14 Vertical stress-strain curves in tension

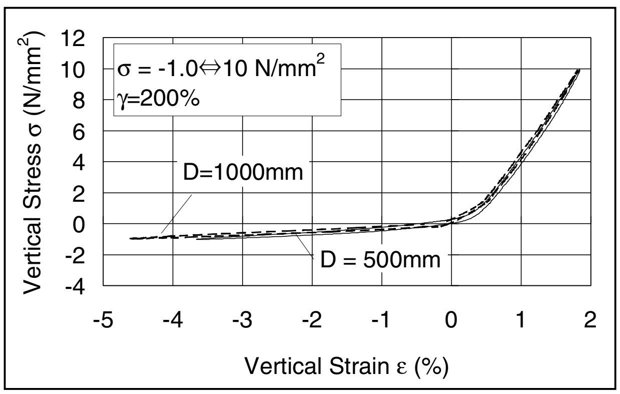


Fig.15 Vertical stress-strain curves

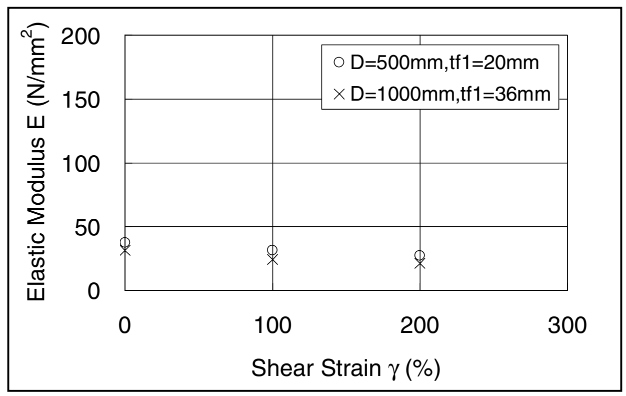
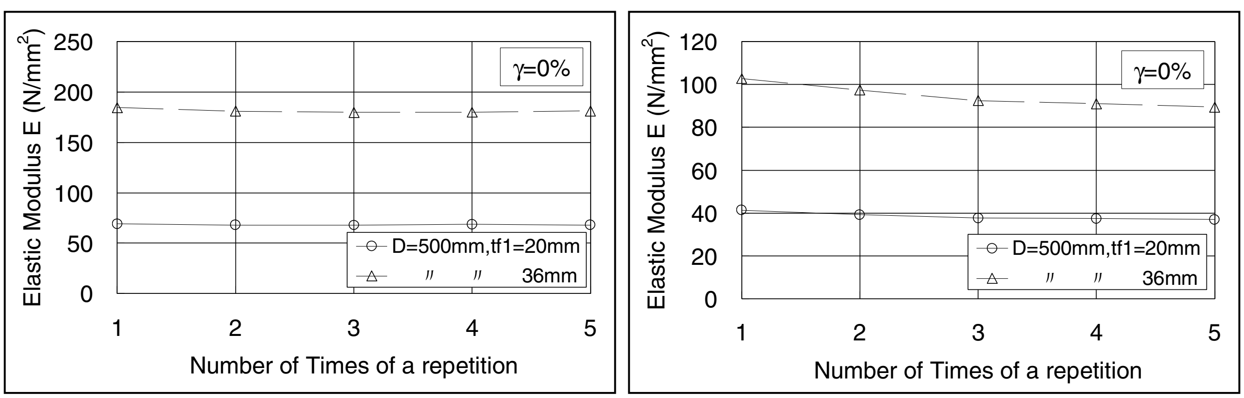


Fig.16 Tensile stiffness for scale effect



(a)σ=-0.5～10N/mm² **(b)σ=-1.0～10N/mm²**

Fig.17 Repeated deformation dependence of E in tension

(2) Shear test under constant tensile deformation

Fig. 18 shows the shear stress-strain curves for the 500mm specimen with the flange plate thickness 20mm with ±250% in shear strain, under the vertical stress 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 than 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 for the 500mm specimen with flange plate thickness 20mm with ±250% in shear strain under the tensile strain of

10 and 25% are almost similar to those under the tensile stress of –0.5 and –1.0N/mm². Fig. 19 and Fig. 20 show the shear stress-shear strain curves and vertical strain-shear strain curves respectively for 500mm specimens with the flange plate thickness 20mm and 36mm with ±250% in shear strain under the tensile stress of –1.0N/mm². The curves for two different flange plate thicknesses show good coincidence in both figures. Fig. 21 shows the shear stiffness (shear modulus *G*) of 500mm specimens with the flange plate thickness 20mm and 36mm as a function of shear strain. 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 tensile stress of –0.5 and –1.0N/mm² respectively. Especially, as the tensile stress of –1.0N/mm² corresponds to tensile strain of 25%, the shear stiffness under these conditions is almost the same.

Fig. 22 and Fig. 23 show the shear stress-shear strain curves and vertical strain-shear strain curves respectively for the 500mm and 1000mm specimens under tensile stress of –1.0N/mm² with shear strain of ±250%. The shear stress-shear strain curves are almost the same. The vertical strain-shear strain curves are a little different, but the vertical stain level is almost the same. Fig. 24 shows the shear stiffness under vertical stress of 15, 0, –0.5 and –1.0N/mm² as a function of shear strain. The result is the same tendency as Fig. 21 for 500mm specimens. Consequently as for the shear stiffness, the scale effect is small. The relation between the number of times of a repetition and the shear stiffness under tensile stress is shown for 500mm specimens with different flange plates in Fig. 25. The tensile deformation is about 2% in tensile strain under tensile stress of –0.5N/mm² or the tensile deformation is about 25% in tensile strain under tensile stress of –1.0N/mm², but change of shear stiffness is very small. The difference of the characteristics as to the flange plate thickness is small.

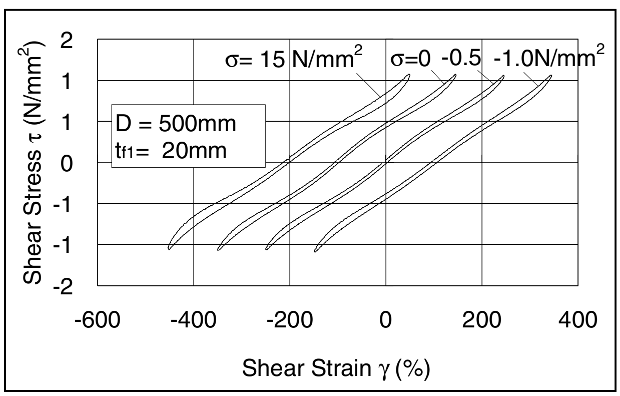
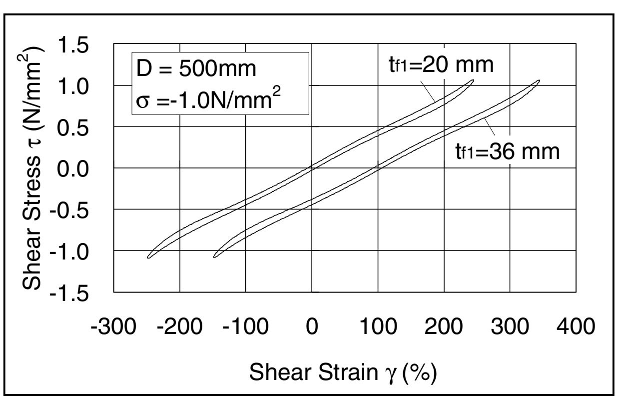


Fig.18 Relation between shear stress-strain curves and tensile condition



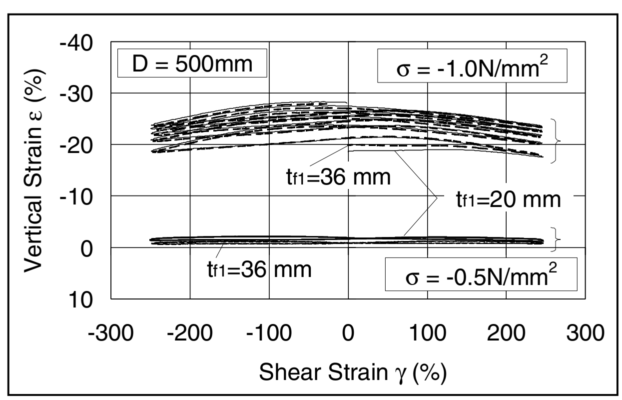


Fig.19 Shear stress-strain curves

Fig.20 Vertical stress-strain curves

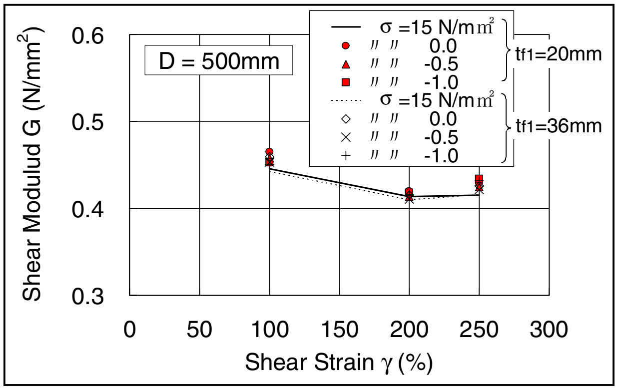


Fig.21 Shear stiffness

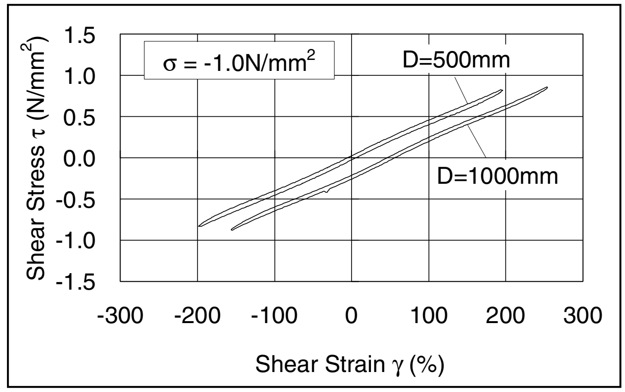


Fig.22 Shear stress-strain curves

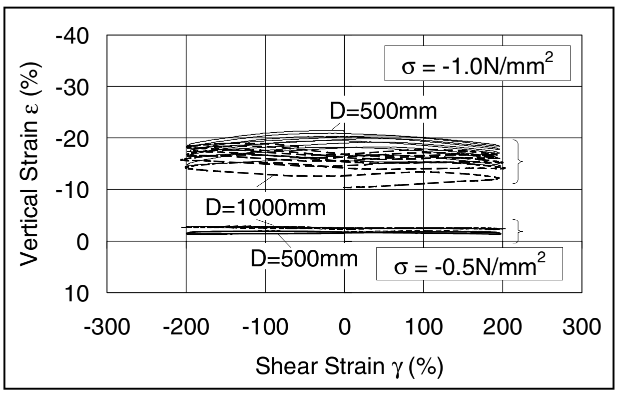


Fig.23 Vertical strain-shear strain curves

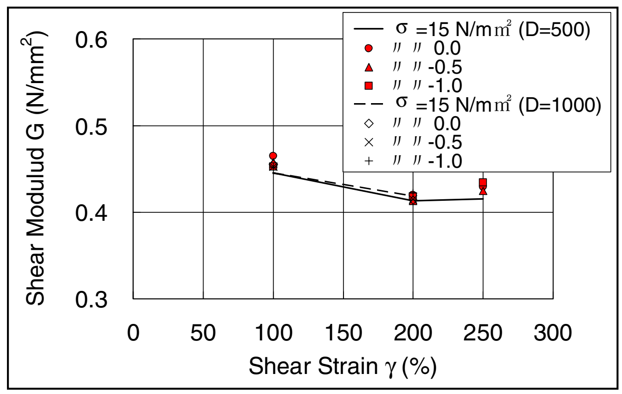
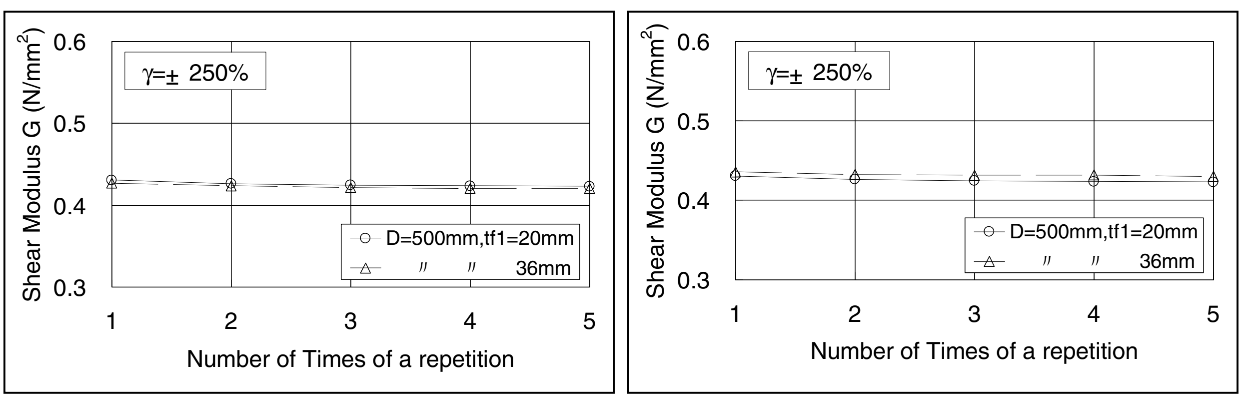


Fig.24 Shear stiffness

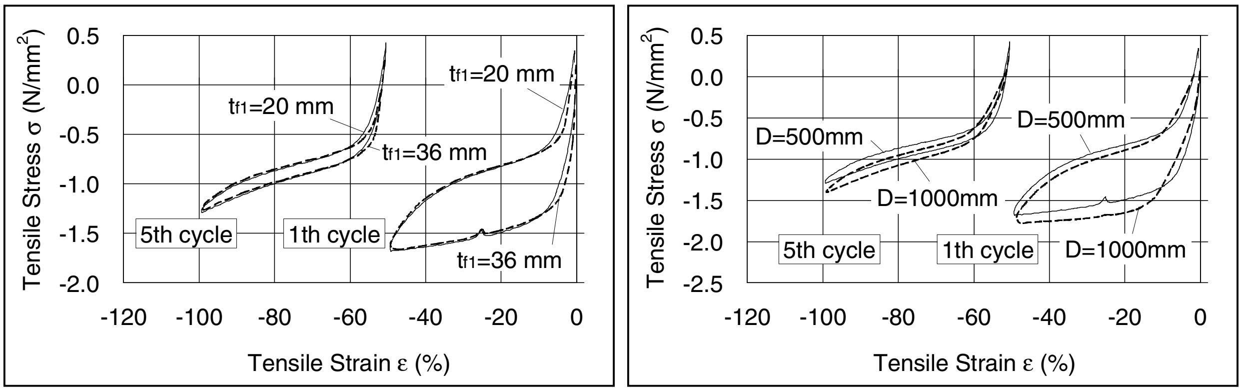


(a)σ=-0.5N/mm² **(b)σ=-1.0N/mm²**

Fig.25 Repeated deformation dependence of G

(3) Simple tensile test

Fig. 26(a) shows the 1st cycle loop and 5th cycle loop obtained by the simple tensile tests for 500mm specimens with the flange plate thickness 20mm and 36mm. 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 that the deformation of the rubber becomes dominant in large deformation and the effect of the flange plate thickness is relatively small. Fig. 26(b) shows the 1st cycle loop and 5th cycle loop obtained the simple tensile tests for 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. The basic characteristics before and after tensile tests are described in Table 4. As the tensile deformation cause the damage in rubber layers, the vertical and horizontal stiffness are fundamentally decreased. But the decreasing ratio of the vertical stiffness is from 2% to 4% and that of the horizontal stiffness is from 3% to 6%.



(a)Effect of Flange plate thickness **(b)Scale effect**

Fig.26 Tensile characteristics in large tension

Table4 Change of basic characteristics after tensile tests

D (mm)	Tf1 (mm)	Condition	Ec (N/mm²)	G (N/mm²)		
				γ=±100%	γ=±200%	γ=±250%
500	20	Initial	1254	0.446	0.413	0.419
		After tensile test A	1203	0.426	0.388	0.399
		After tensile test B	1215	0.433	0.389	0.398
500	36	Initial	1215	0.443	0.410	0.416
		After tensile test A	1230	0.426	0.385	0.395
		After tensile test B	1192	0.430	0.387	0.395
1000	36	Initial	1213	0.445	0.419	0.423
		After tensile test A	1190	0.434	0.400	0.413
		After tensile test B	1199	0.432	0.396	0.408

(4)Deflection of the flange plate

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 by equation (3) and equation (4).

When $0 \le r \le b$

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

When $b \le r \le a$

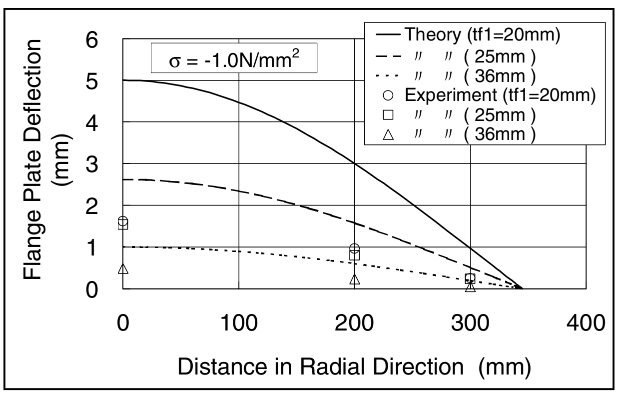
$$\delta = \frac{pb^4}{16D}\left[\frac{1}{2(1+\nu)}\left(1-\frac{r^2}{a^2}\right)\left\{2(3+\nu)\frac{a^2}{b^2}-(1-\nu)\right\} - \left(1+\frac{2r^2}{b^2}\right)\ln\frac{a}{r}\right] \tag{4}$$

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.

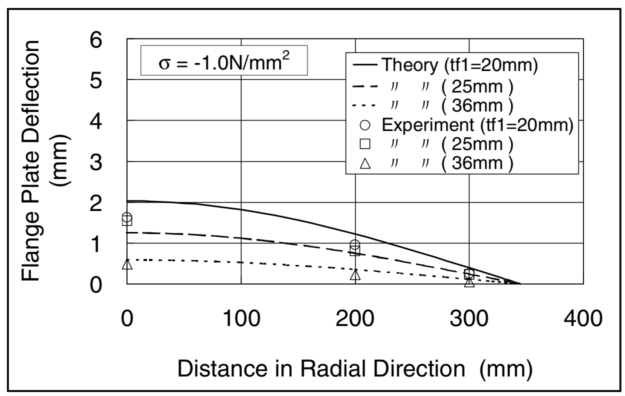
Fig. 27(a) shows the calculated values (shown as the lines) and measured values (shown as the symbols) for the flange deflection with respect to the radial distance from the center. Theoretical values are much greater than measured ones. So, it takes the thickness of the connecting plate into consideration and the equivalent thickness of the flange plate is attempted to apply to theoretical equation. The equivalent thickness is made the thickness of the flange plate added to the additional flange plate thickness. The additional flange plate thickness Δt is calculated by equation (5).

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

where D_r: diameter of connecting plate, D_{fp}: PCD(Pitch Circle Diameter) of fastening bolts. t_r' : thickness of connecting plate from upper surface of the flange plate upwards, tr' of 500mm and 1000mm specimens are 12mm and 20mm respectively. Fig. 27(b) shows the modified theoretical values using equation (5). That shows good correspondence to measured result. From these results, it seems possible that flange deflection is evaluated by using the equivalent flange thickness.



(a)Before modified



(b)After modified

Fig.27 Deflection of flange plate

5.CONCLUSION

From these experimental results, the following conclusions are obtained,

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

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

(3) The tensile stiffness is sensitive to the flange plate thickness.

(4) It became clear that the shear stiffness is 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 in tensile stress (corresponding to about 25% in tensile strain).

(5) The scale effect in small tensile deformation (about -1.0N/mm^2 in tensile stress) is small.

(6) It may be possible to reduce the tensile deformation of the part of rubber by using thin flange plate. But it is necessary to study the distribution of the stress or strain in laminated rubber bearing.

(7) The deflection of the flange plate is evaluated by using the equivalent flange plate thickness and the simple formula.

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

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