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EXPERIMENTAL STUDY ON THE EFFECT OF TENSION FOR RUBBER BEARINGS

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SUMMARY

This paper presents the experimental results from the tension loading of laminated rubber bearings. The total 16 rubber bearings including a natural rubber bearing, a high damping rubber bearing and a lead-plug rubber bearing were used in these experiments. The tension tests were carried out from the condition where gave the offset shear deformation. The maximum tensile deformation was 100% in tensile strain. The change of basic characteristics was checked by characteristic tests enforced before and after each tension loading. Tension hysteresis curve showed the non-linear characteristics as tensile strain increased. Even if 100% in tensile strain was given with offset shear strain of 200%, rubber bearings did not rupture. It was not clarified the obvious differences to compression and shear characteristics before and after the tension loading, although it was conceivable that the internal voids (cracks) associated with three axial tensions have occurred in rubber layers. These experimental results of tension loading in displaced position present the effective data to the design of a seismic isolated building.

INTRODUCTION

The laminated rubber bearing is mainly used as the isolator for base-isolated buildings. In the design of a base-isolated building, it is important to evaluate the performance of a rubber bearing. The characteristic evaluation factor of a rubber bearing is roughly divided into compression, shear property and tensile characteristics. The test data on compression characteristics and horizontal characteristics is accumulated on sufficiently evaluating the ultimate capacity. However, there is currently little data available on tensile characteristics. Until now, the height of the base-isolated building was low, and the level of an earthquake ground motion for dynamic design was also small. However, after the Hanshin-Awaji Earthquake disaster, seismic isolation systems for large-scale structures like a high-rise buildings, etc. began to be adopted, and in addition, a design case of increasing the level of an earthquake motion is increasing. In such cases, it must be allowed that the large tensile force affects the rubber bearing caused by the overturning moment and the vertical ground motion. Therefore, the performance as the rubber bearing received tensile force is exactly evaluated, and it is important that this tensile characteristics reflect on structural design. The technical committee of JSSI, Japan Society of Seismic Isolation, and manufacturers for rubber bearing carried out cooperatively the tensile tests on the laminated rubber bearings. In the tensile test, the tensile deformation was given from the condition that the shear strain was retained. This paper presents the results from these tensile tests of rubber bearings.

TEST SPECIMENS

Three types of specimen, a natural rubber bearing (NRB), a high damping rubber bearing (HDR) and a lead-plug rubber bearing (LRB) were used for the test specimen. In Table 1, which shows the dimensions of the test specimens, these three types are subdivided into seven types according to manufacturer: three types of both NRB

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and HDR, and one of LRB. The diameter of the test specimens is about 500mm except TH, YH specimens, and the primary shape factor (S_1) is about 30 except TH specimen, and the secondary shape factor (S_2) is about 5 for all specimens. A Lead plug (90ϕ) was filled in a center hole of OL specimen. In this test, one specimen was used for a case of one offset shear strain. The offset shear strain was set within 0〜300% in order to include 200%. The total number of specimens was 16. The first character of the specimen's name shows the manufacturer name (6 manufacturers), and the next character shows the type (3 types) of the specimen. The amount of the offset shear strain is shown, when there is a numeral as the third character. For example, "KN2" show the NRB specimen of the K manufacturer, and the offset shear strain is 200%. Tables 2 shows the rubber mixture and rubber physical property of each test specimen. The shear modulus of the rubber material of BH,YH specimens was 6kg/cm^2, and for the other, it was about 4kg/cm^2. In the rubber mixture of NRB, the proportion of the elastomer was more than 70%, but in HDR, it became 50% or less. Figure 1 shows the connection between the main body (the end steel plate) and the flange plate of the specimen. The flange plate was joined to the end plate by the use of bolts for all specimens. The transmission of the shear force was classified into two methods: 1) putting the shear key between the end plate and the flange plate, and 2) embedding the end plate shallowly in the flange plate. Table 3 shows the size of the flange plates and the bolt interval (Pitch Circle Diameter). The test specimen was fixed to the testing machine by 8 bolts in the flange plate. Finite element analysis (FEM) was carried out in order to evaluate the out-of-plane bending stiffness of the flange plate and the end plate. The analytical model in which the flange plate (PCD2 in diameter) and the end plate (PCD1 in diameter) were integrated in one body was used. The analytical model was perfectly fixed at the 8 positions of bolt, and the concentrated vertical load (1ton) was given to the center. The material property of steel was elastic. Table 3 shows the out-of-plane stiffness calculated from the maximum deflection at the center of the model. From this results, the bending stiffness of BN,BH,OL specimens is the highest, and that of the SN,KN is the lowest. The difference is more than 4 times. According to the elastic theory, the deflection of a circular plate supported at the circumference is in proportion to the square of the radius and is in inverse proportion to the cube of the thickness. The deflection could be increased severely by the relation between the diameter and the thickness of the flange plate, when the size of the laminated rubber bearing increases.

TESTING METHOD

In this test, the constant tensile strain was loaded from the condition that the offset shear deformation was retained. In the first step, the initial characterization tests were carried out. The compression test and the compressive shearing test were included in the initial step. In the compression test, 5 cycles of loading was applied up to 200 (or 150) kg/cm^2 in compressive stress. In the compressive shearing test, 5 fully reversed cycles to a peak deformation of 100% in shear strain was applied without a vertical load, and continuously 5 fully reversed cycles of 100% and 200% was applied for compressive stress of 100kg/cm^2. The pre-loading was carried out in order to stabilize the hysteresis behavior for HDR (BH,YH,TH specimens). Though the pre-loading content was a little different for each specimen, the basic loading was a several fully reversed cycles of 200% or 300% in shear strain under a compressive stress of 100kg/cm^2. In the second step, the offset shear strain was given, and it kept that condition. In the third step, 10cycles of the first tensile strain of 5% was given. In the fourth step, the offset shear strain was once returned to 0 point. In the fifth step, compression tests, tensile tests and compressive shearing tests were carried out as the basic characteristic tests at this sequence in order to investigate a characteristic change after the tensile strain was experienced. The content of compression tests and compressive shearing tests was same as the initial characterization tests. In the tensile test, 5 cycles of the tensile strain of 5% was applied in order to examine the tension characteristic. After the basic characteristic tests, it returned to the second step, and series of the test were repeated by the increment of the tensile strain corresponding to 10, 25, 50, 75 and 100%. The speed in the tension loading was about 1〜8mm/s. However, the given tensile strain (tensile deformation) did not exactly agree with the tensile strain of the rubber layers so that the flange plate of specimen may generate the bending deformation. In the tension loading, the stiffness and the elastic limit load *Pt* were obtained based on the hysteresis loop of cycle 1 as shown in Figure 2. The initial stiffness *Kt1* was obtained by connecting the loading start point with the tensile load corresponded to the shear modulus *G*. The elastic limit load *Pt* was obtained from the intersection point with the hysteresis loop in shifting the initial gradient to the deformation corresponded to the tensile strain of 1%. In the compression test, the compressive stiffness *Kc* was calculated for the three load ranges (*0-0.1P-0.5P-P*, *P*: Max. Load) based on the hysteresis loop of cycle 4. The effective stiffness *Ke* and the energy dissipation *E* in compressive shearing tests were calculated based on the hysteresis loop of cycle 4.

Table 1 Dimensions of Rubber Bearings

Name	Types	*D* (mm)	*d* (mm)	*tr* (mm)	*n*	*ts* (mm)	S_1	S_2	*tc* (mm)	Offset Shear Strain(%)			
SN	NRB	500	20	3.75	26	3.2	32	5	--			200	300
KN	NRB	500	0	3.75	26	3.2	33	5	--	0	100	200	
BN	NRB	504	0	4.2	24	3.1	30	5	8			200	300
BH	HDR	504	0	4.2	24	3.1	30	5	8			200	300
YH	HDR	600	30	4.5	26	3.2	32	5	10	0		200	300
TH	HDR	400	16	2.4	33	3.2	40	5	10	0		250	
OL	LRB	500	90	4.0	25	3.1	31	5	10	0		200	

D: Bonded Diameter of Rubber Layers, *d*: Center Hole Diameter, *tr*: Rubber Thickness,
n: Number of Rubber Layers, *ts*: Steel Shims Thickness, *tc*: Cover Layer Thickness,
S_1 (Primary Shape Factor) and S_2 (Secondary Shape Factor) defined as follows:

$$S_1 = \frac{D}{4tr}, \quad S_2 = \frac{D}{ntr}$$

Table 2 Rubber Properties and Chemical Compounds

Name	Shear Modulus (kg/cm^2)	Hardness (JIS-A)	Tensile Strength (kg/cm^2)	Ultimate Elongation (%)	Compound (wt%)			
					Elastomer	Filler	Vulcanizing Agent	Others
SN	4.5	40	220	680	75	15	6	4
KN	4.5	38	267	680	75	11	8	6
BN	4.0	37	□170*	□600*	66	12	7	15
BH	6.0	60	□80*	□800*	48	24	9	19
YH	6.0	70	143	750	40	33	1	26
TH	4.0	47	□110*	□700*	47	33	12	8
OL	4.0	37	270	730	71	14	7	8

*Manufacturer's Standards

Table 3 Dimensions of End Plates and Flange Plates

Name	Attaching Method (Fig.1)	End Plate			Flange Plate			out-of-plane Stiffness* □t/mm□
		D1 (mm)	t1 (mm)	Bolt Hole P.C.D.1(mm)	D2 (mm)	t2(t3) (mm)	Bolt Hole P.C.D.2(mm)	
SN	Type-2	520	16	440	800	25(21)	720	20.0
KN	Type-2	525	16	400	800	25(21)	690	21.3
BN,BH	Type-1	516	34	450	710	25	625	86.2
YH	Type-2	620	34	530	880	30(26)	770	64.9
TH	Type-1	400	25	300	700	25	550	54.6
OL	Type-1	500	31	400	700	30	600	102.0

*The Stiffness was calculated by loading the unit vertical load at the center of FEM model composed of a flange plate and a end plate.

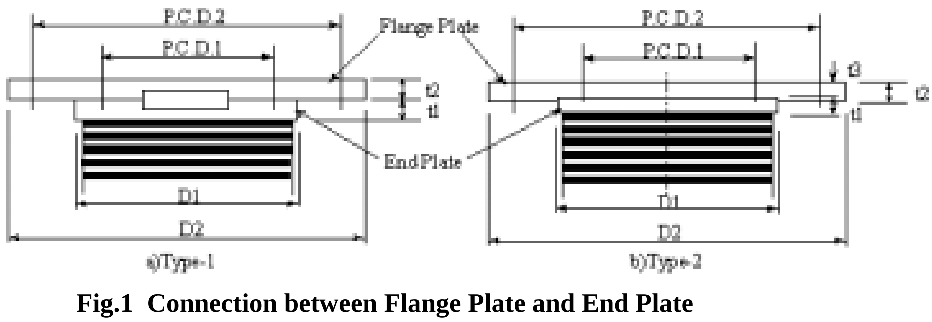

Fig.1 Connection between Flange Plate and End Plate

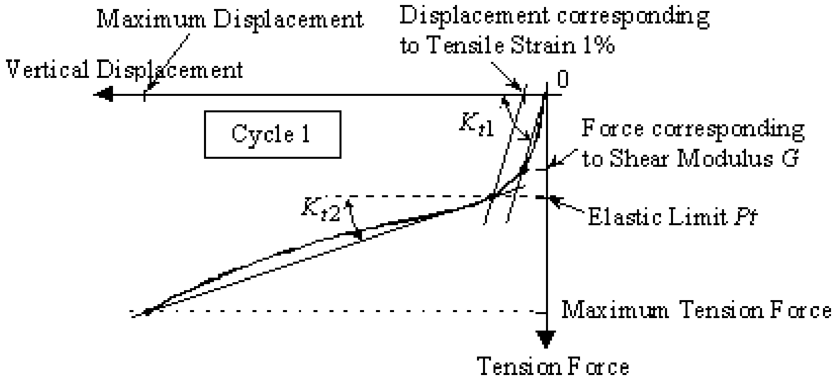

Fig.2 Evaluation of the Stiffness in Tension Loading

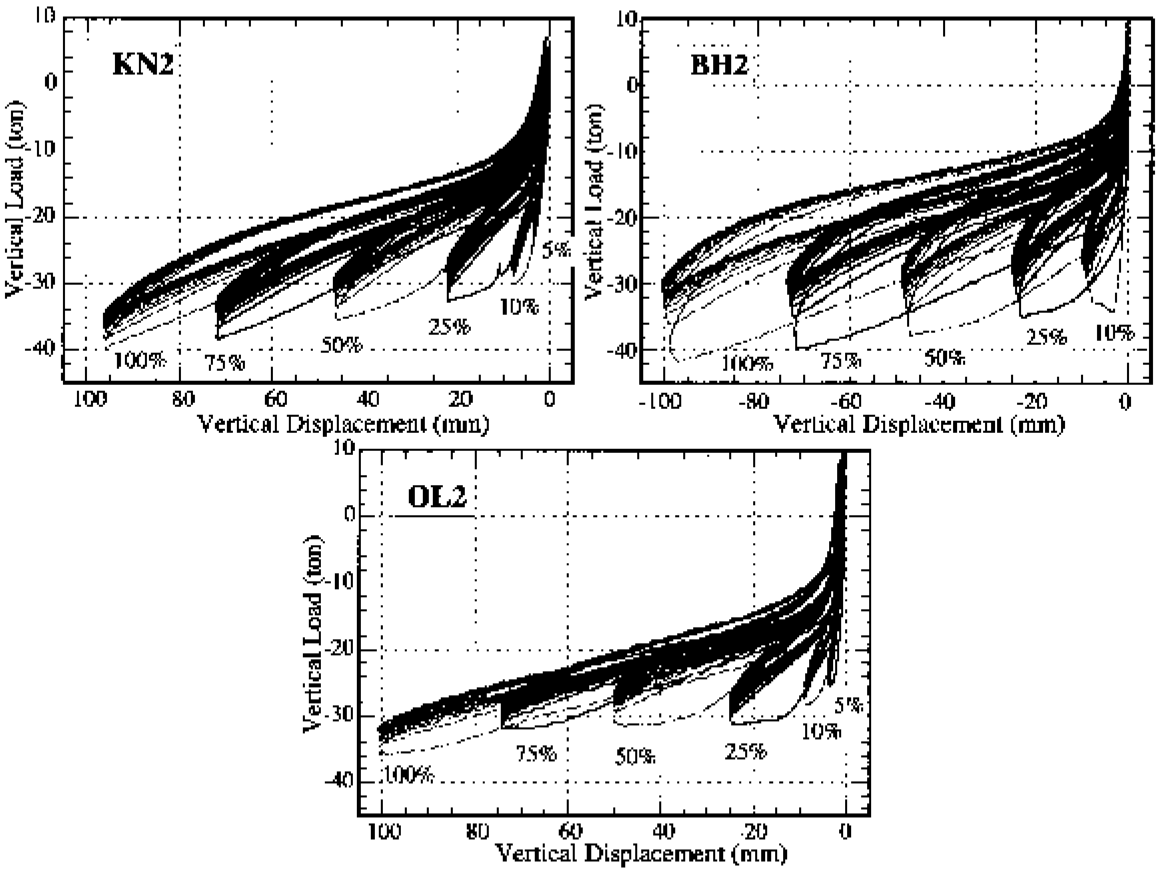

Fig.3 Hysteresis Loop of Tension Loading

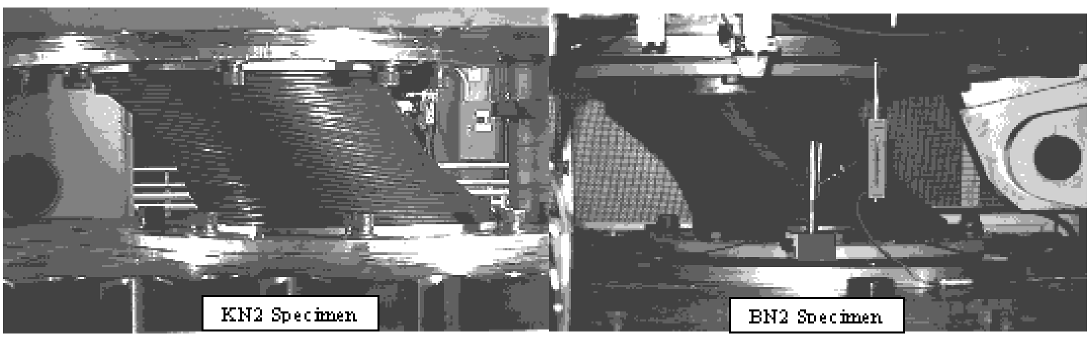

Photo.1 Maximum Deformation in Tensile Strain of 100%

EXPERIMENTAL RESULTS

Characteristics in Tension

Figure 3 shows the hysteresis loop of tension loading with shear strain of 200% for KN2, BH2 and OL2 specimens. Force and displacement of the tension direction are shown negative. The hysteresis loop shows the linear behavior up to 10% in tensile strain. When the tensile strain exceeds 25%, the tension rigidity is greatly decreased, and the hysteresis loop shows the bi-linear loop. Photograph 1 shows KN2, BN2 specimens 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 shim steel plates generate the rotation by the increase of the bending deformation of the rubber layers. The strain distribution of the upper and lower rubber layers is not uniform under shear deformation. Figure 4 shows the envelope of the hysteresis loop for a each offset shear strain. When the offset shear strain increases, the tensile load seems to increase, since the strain hardening of the rubber material is also stronger. In the SN,BN,BH specimens, such tendency is observed. Reversibly, in other test specimens, the tensile load decreases as the shear strain increases. Especially in TH and OL specimen, the tensile load decreases as the tensile deformation increases. It is difficult to simply compare for the reason why such difference happens, since the rubber material is obviously related. The effect by repeating the tension loading in many cycles will be one of the reasons. Figure 5 shows the initial stiffness $Kt1$ and the secondary stiffness $Kt2$ calculated from the tension hysteresis loop. The initial stiffness shows a smaller value from 1/5 to 1/10 in comparison with the compressive stiffness. In the region of which the tensile strain is large, the secondary stiffness is about 2 to 4t/cm, and it can be considered the value which is very near for 0, if it is compared with the compressive stiffness. The tension stiffness decrease in most cases, as the tensile strain increases. However, in the BH,BN specimens, such tendency is small, and the initial stiffness is higher than that of other test specimens. The initial stiffness of OL specimen shows the highest value when the tensile strain is low. Figure 6 shows the relationship of the elastic limit load Pt to the tensile strain. The load Pt decrease as the tensile strain increases. While the decreasing rate for NRB is around 25%, it is a bigger rate of 30% to 50% for HDR and LRB specimens. Though it is considered that the effect of the rubber material is big for the cause of such difference, the difference of the bending stiffness of flange plate (refer table 3) and the effect by the central hole and cover rubber layer can not be disregarded either. By the effect of the bending deformation of the flange plate, it is clear that the tensile strain of the rubber layer is not uniformly distributed in radial direction. It is necessary to wait for future experiments and storage of analytical data about the effect on the damage (void) in rubber layer by the flexibility of the flange plate and the central hole etc.

Basic Characteristics after Tension Loading

Figure 7 shows an example of the results of the compression test in the basic characteristic tests. Similarly, Figure 8 shows for the tensile test, and Figure 9 shows for the compressive shearing test (compressive stress of 0kg/cm^2, shear strain of 100%). From the hysteresis behavior in the compression, the increase of the compressive displacement and the decrease of the stiffness are observed in the region where the compressive load is low. In the tensile test, the maximum tensile strength decrease to about half, after the large tensile strain is experienced. It is shown that the damage (crack) was generated in the rubber layers, as the large tensile strain was received. In the hysteresis loop in the compressive shearing tests, there is only a little change at the horizontal stiffness and the hysteresis loop area. Figure 10 shows the relationship between the compressive stiffness and the tensile strain. The tensile strain of 0% means the result of the initial performance tests. Though the decrease of the stiffness in the region where the compressive load is high is not observed, the stiffness in the low load region decrease as well as observing even in the hysteresis loop of the compression. In this experiments, the compression tests were carried out in the load control, after the tension loading was carried out by the displacement control. It can be estimated that the stiffness may decrease in order to condense the expansion by the compression loading after the height of the rubber bearing increase by the tension loading (the rubber material expands). Therefore, the residual displacement in the compression hysteresis loop seems to correspond to the height increment of the rubber bearing. Figure 11 shows the relationship between the effective stiffness and the tensile strain in the compressive shearing tests. The effective stiffness is fundamentally decreases with the increase of the tensile strain. The decreasing ratio is from 4 to 14%, though the decrease of the effective stiffness in the compressive stress of 0kg/cm^2 is bigger than the that of 100kg/cm^2. It will be influenced by the friction that the stiffness change is not more remarkable when the compressive load exists. Figure 12 shows the relationship of the hysteresis loop area to the tensile strain for HDR and LRB. It tends to be similar to the effective stiffness for the hysteresis loop area. The decreasing ratio of the hysteresis loop area in the compressive stress of 0kg/cm^2 for OL2 specimen is big, and it is about 23%.

CONCLUSIONS

This paper presents the experimental results of the tensile test with the offset shear strain which used 16 rubber bearings of 7 types. From these experimental results, the following conclusions were obtained:

1) Tension hysteresis curve shows the elastic characteristics until the tension stress reach around the elastic modulus of rubber material. The elastic tensile strain in this experiment is about 5 to 10%.
2) Non-linear characteristics of the bi-linear hysteresis type are shown, as the tensile strain increases. Even if 100% in tensile strain is given with offset shear strain of 200%, the laminated rubber bearings do not rupture.
3) Although it is conceivable that the internal voids associated with 3 axial tensions have occurred in rubber layers, obvious differences in compression and shear characteristics were not observed. The reason for this have not yet clarified because the shear force may be transmitted by the friction of rubber material. It is necessary to evaluate the effect of this damage on the lateral deformation capacity and the aging, and also to quantify the size and the area of the damage part in rubber layers.

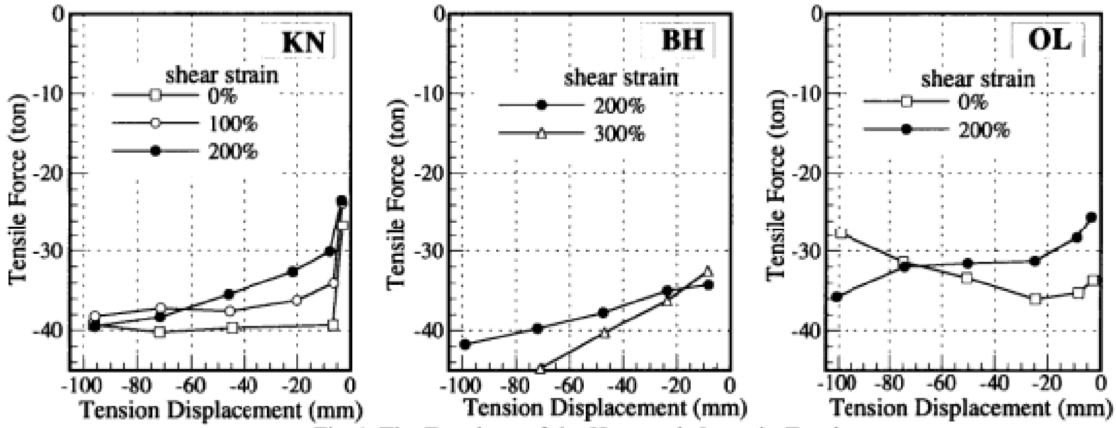

Fig.4 The Envelope of the Hysteresis Loop in Tension

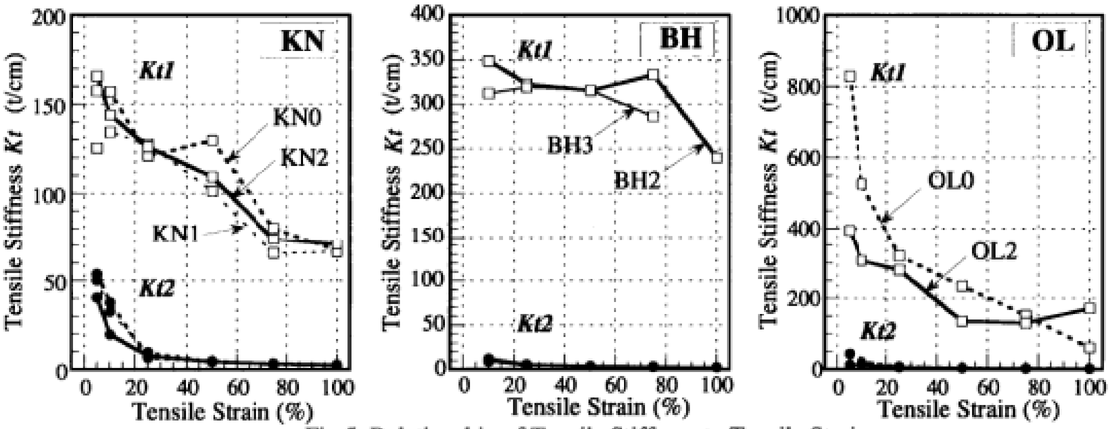

Fig.5 Relationship of Tensile Stiffness to Tensile Strain

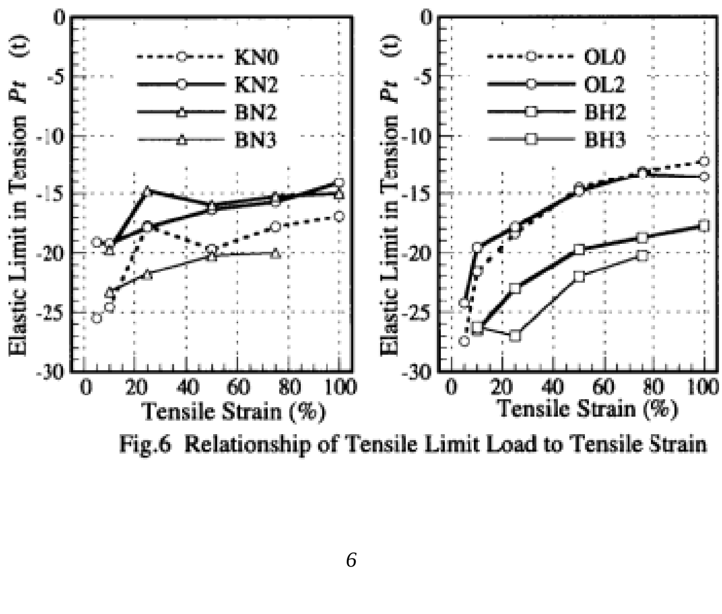

Fig.6 Relationship of Tensile Limit Load to Tensile Strain

4) These experimental results of tension loading in displaced position present the effective data to the design of a seismic isolated building. But, In these tests, only one test specimen for the each loading case is used in order to collect the experimental data widely. It is required that test data is accumulated more and more by also considering the scale effect in the size of rubber bearing.

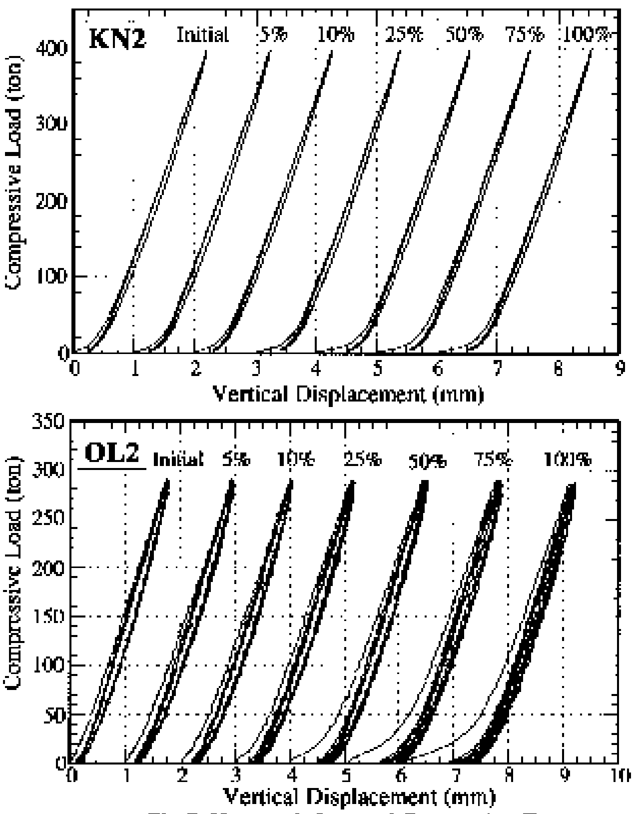

Fig.7 Hysteresis Loop of Compression Tests

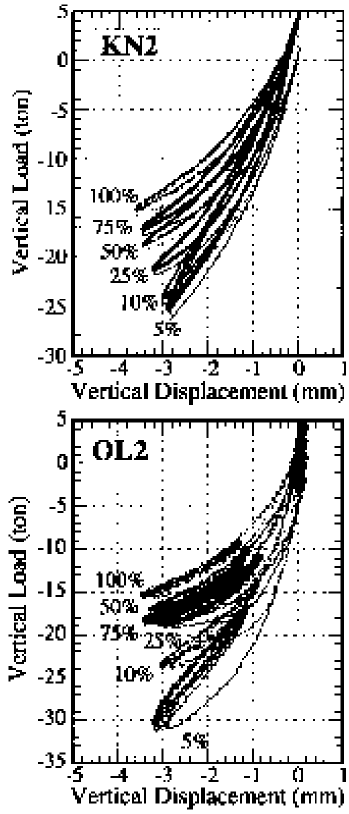

Fig.8 Hysteresis Loop of Tension Tests

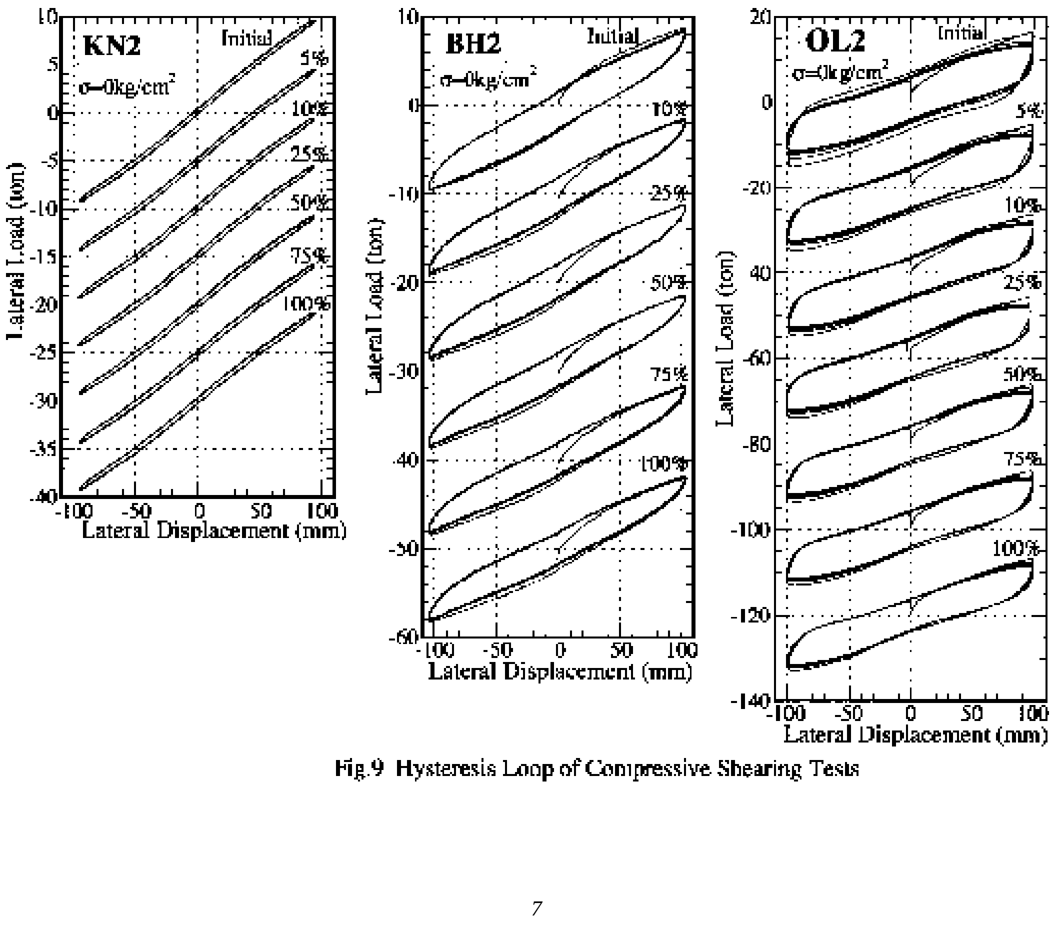

Fig.9 Hysteresis Loop of Compressive Shearing Tests

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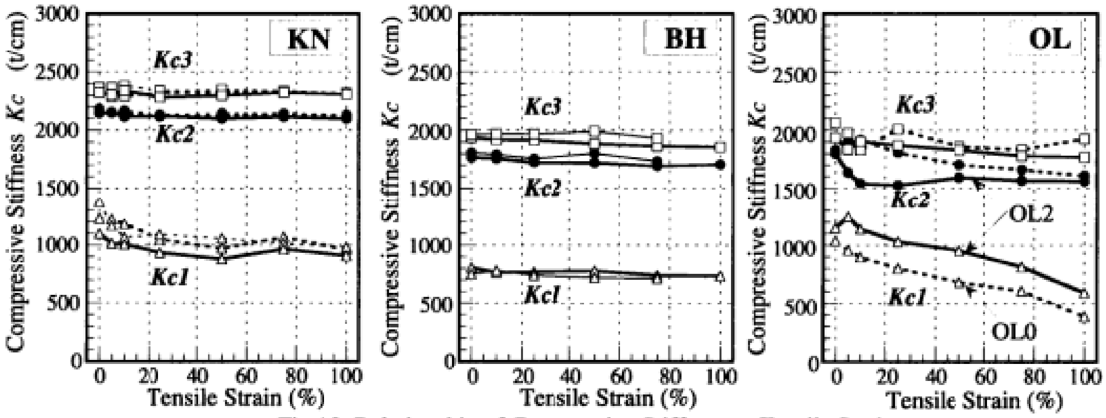

Fig.10 Relationship of Compressive Stiffness to Tensile Strain

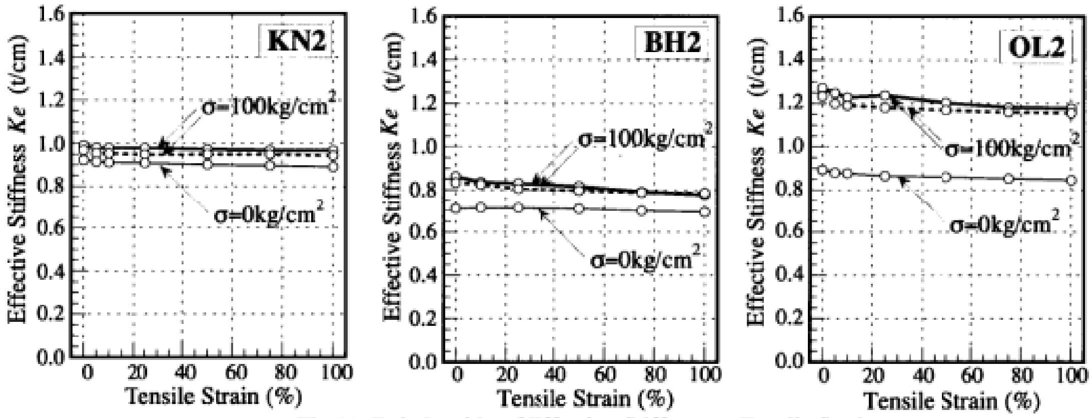

Fig.11 Relationship of Effective Stiffness to Tensile Strain

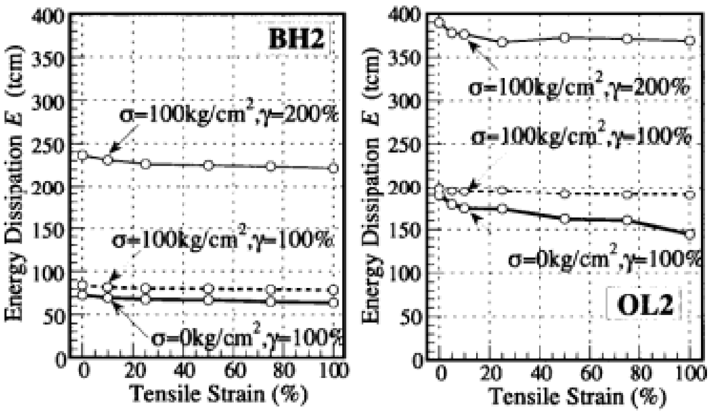

Fig.12 Relationship of Energy Dissipation to Tensile Strain