DEVELOPMENT AND APPLICATION OF SYSTEM TO REDUCE THE EXCESSIVE TENSILE FORCES ARISING IN LAMINATED RUBBER BEARING

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Abstract

This paper describes the development of a new system for reducing tensile forces generated in laminated rubber during an earthquake. In Japan the adoption of seismically isolated buildings is increasing to reduce damage to the structure of buildings during a large earthquake, even among tower-like buildings. In these cases excessive tensile forces are generated in the corner columns and in the laminated rubber bearings directly below these columns, due to overturning moments during an earthquake, and this was an issue for seismically isolated buildings using laminated rubber bearings whose tensile load resistance is small. The “TOS System” was developed in order to reduce these tensile forces generated in laminated rubber bearings.

The TOS System is a mechanism that includes the “Laminated rubber bush” embedded in concrete above the laminated rubber bearing, and the bush and a flange plate of the laminated rubber bearng are connected by bolts.The Laminated rubber bush with rubber and metal laminated in a circular cylindrical form can be deformed flexibly in the vertical direction thereby reducing the tensile forces, while enabling the horizontal forces to the transmitted to the laminated rubber bearing.
Element tests were carried out on the Laminated rubber bush, and full-size laminated rubber bearing loading tests were carried out using the TOS System. In each case it was confirmed that the test results satisfied the target performance.

Then a tower-like seismically isolated building of height about 100 m was realized by the application of the TOS System.

Introduction

There is an increasing need in Japan a seismically isolated buildings, which greatly reduces the damage to buildings in major earthquakes. The number of cases of seismically isolated buildings being planned is increasing, even among buildings with high aspect ratio (height to width ratio). In this case the overturning moment produced during an earthquake increases, which generates an excessive tensile force on the seismic isolator. Also, normally the tensile stress on the seismic isolator is designed to be less than 1.0 [N/mm2] taking into consideration the horizontal motions and vertical motions of the seismic motion, so this has become an issue in the design of seismically isolated buildings with high aspect ratio. As a method of solving this issue, the "TOS System" has been developed as a new method of relieving the tensile forces to deal with uplift in seismic isolation.

In the TOS System, instead of installation bolts connecting the seismic isolation foundation of the upper structure and the flange plate of the seismic isolator, the connection is made using a laminated rubber bush. In this way when tensile forces are produced by the horizontal motions and vertical motions during an earthquake, the rubber within the laminated rubber bush deforms in shear, which reduces the tensile forces on the seismic isolator. This paper describes the TOS System in outline, and the results of tests.

FEATURES OF THE TOS SYSTEM. The TOS System has a simple configuration consisting of a "bush installation steel tube" embedded within the upper footing, and a laminated rubber bush having an uplift mechanism fixed to the bush installation steel tube by screwing together, with the laminated rubber bush and the seismic isolator flange plate attached by bolts. The laminated rubber bush with the uplift mechanism has a cylindrical shape formed by laminating rubber and steel tubes, it exhibits flexible and stable behaviour with respect to tensile forces, and at the same time it is a mechanism that can transmit shear forces. In addition, by screwing a stopper plate onto the laminated rubber bush, when excessive axial forces are produced, a metal outer ring of the laminated rubber bush contacts the stopper plate, so excessive uplift deformation can be restrained.

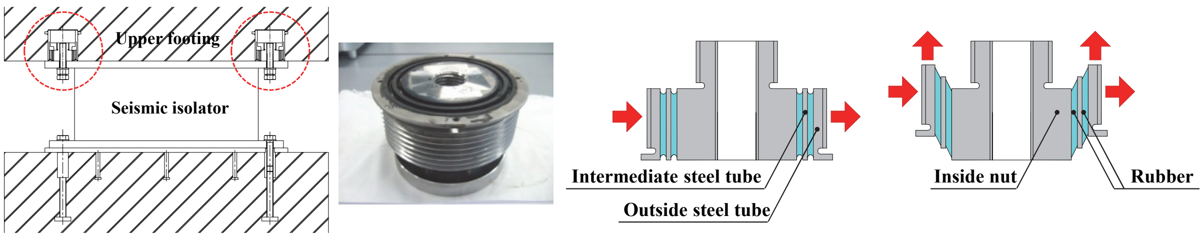


Figure 1. TOS System installation position and outline of the laminated rubber bush.

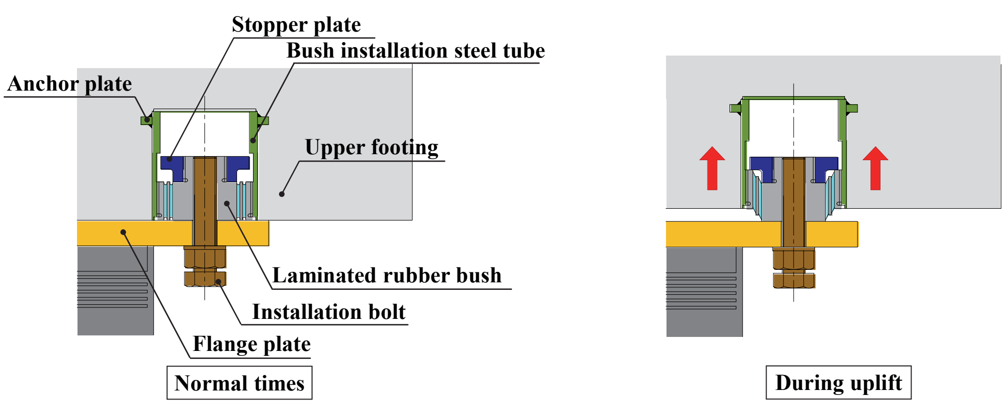


Figure 2. Member configuration of the TOS System.

The following are the features of the TOS System configured from the members as described above.

1) Highly stable uplift properties are realized by using the laminated rubber bush, and with this mechanism shear forces can also be transmitted during uplift.

2) When an excessive tensile force is produced, the metal outer ring of the laminated rubber bush and the stopper plate contact, so it is possible to restrain excessive uplift deformation.

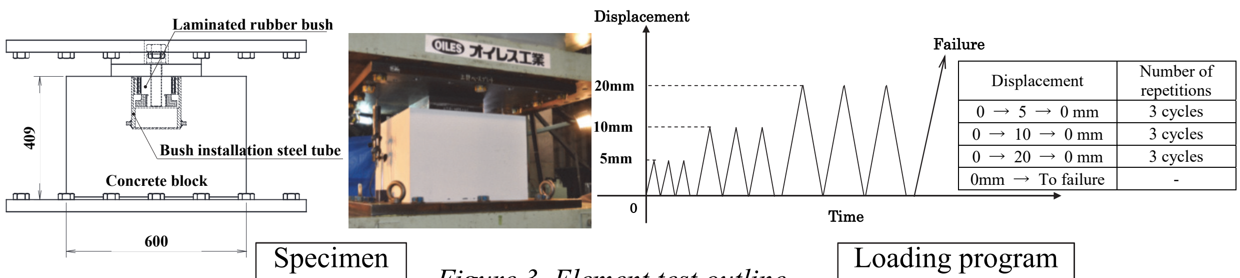
3) Because of embedding the uplift mechanism in the concrete structure side (footing side), there is no interference between the uplift mechanism and the seismic isolator during shear deformation. Therefore, there is no need to increase the size of the flange plate or the footing.

4) Joining is carried out by screwing in and tightening bolts, so installation is easy. When the seismic isolators are to be replaced, the laminated rubber bush can be removed, so the TOS System can be checked and replaced.

5) The uplift mechanism is provided on the upper side of the seismic isolation device, so it is difficult for water to penetrate into it, so high durability is expected.

ELEMENTS TESTS. Tensile stiffness confirmation tests and failure property confirmation tests were carried out using the TOS System on its own (element test specimens), in order to check the tensile stiffness and failure properties during large deformation of the TOS System on its own. The test outline is shown in Figure 3. The element test specimens were produced by casting the bush installation steel tube into a concrete block, and screwing the laminated rubber bush into the bush installation steel tube. Note that when 20 mm of tensile displacement is generated, the outer ring of the laminated rubber bush and the stopper plate come into contact.

Element tests were carried out on 4 test specimens. In the loading program, tensile displacements of 5, 10, and 20 mm were carried out for 3 cycles each, following which the tensile displacement was increased until failure of the test specimen, in order to confirm the failure properties.



Displacement	Number of repetitions
0 → 5 → 0 mm	3 cycles
0 → 10 → 0 mm	3 cycles
0 → 20 → 0 mm	3 cycles
0mm → To failure	-

Figure 3. Element test outline.

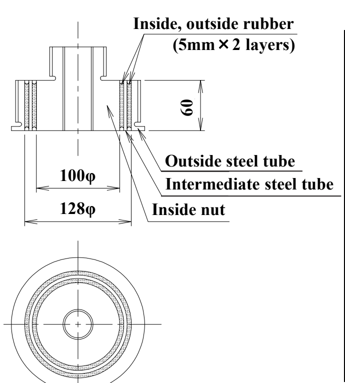
Figure 4 shows the dimensions of the laminated rubber bush used in the test specimens. The tensile stiffness ${}_tK_b$ of the laminated rubber bush can be represented by the following equation [1].

$$\frac{1}{{}_tK_b} = \frac{1}{{}_tK_{b1}} + \frac{1}{{}_tK_{b2}} \tag{1}$$

${}_tK_{b1}$: Rubber tensile stiffness of the 1st layer [kN/mm]
${}_tK_{b2}$: Rubber tensile stiffness of the 2nd layer [kN/mm]

$${}_tK_{bi} = \frac{2\pi \cdot G_b \cdot H_{bri}}{\log_e \dfrac{r_{boi}}{r_{bii}}} \tag{2}$$

${}_tK_{bi}$: Rubber tensile stiffness of the i th layer [kN/mm], H_{bri}: Rubber height of the i th rubber [mm]
r_{boi}: External radius of the i th rubber [mm], r_{bii}: Internal radius of the i th rubber [mm]
G_b: Elastic shear modulus of the rubber [N/mm2]



Rubber elastic shear modulus		0.78 [N/mm^2]
Inside rubber	Internal radius	50 [mm]
	External radius	55 [mm]
	Height	60 [mm]
	Tensile stiffness	3.09 [kN/mm]
Outside rubber	Internal radius	59 [mm]
	External radius	64 [mm]
	Height	60 [mm]
	Tensile stiffness	3.61 [kN/mm]
Tensile stiffness		1.66 [kN/mm]

Figure 4. Laminated rubber bush dimensions.

Figure 5 shows the tensile load - tensile displacement relationship (test specimen No. 2), obtained in the tensile stiffness confirmation test. Regardless of the volume of tensile deformation, the load-displacement relationship was stable with the tensile stiffness in the second and subsequent cycles lower than in the first cycle. This trend was the same as the repetition dependency during horizontal loading of the seismic isolator [2]. Regarding the effect of tensile displacement, there was good agreement with the theoretical value of tensile stiffness.

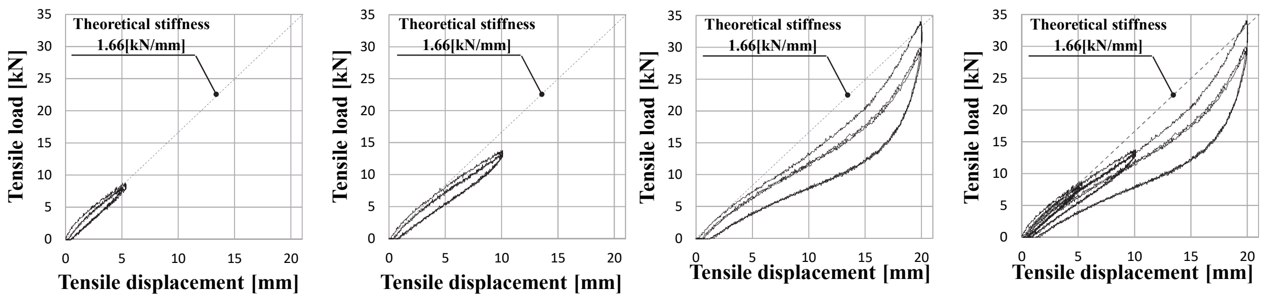


Figure 5. Tensile load - tensile displacement relationship (Element test specimen: No.2).

Figure 6 shows the results of the large displacement failure property confirmation tests. In the process up to failure, in the beginning, stable behavior was exhibited by elastic deformation of the laminated rubber bush, and at a tensile displacements of 20 mm the stopper plate and the laminated rubber bush outer metal ring came into contact, so the stiffness increased. After the tensile load reached about 450 kN, cracking in the concrete progressed and a great reduction in the load resistance was found, so the test was terminated. Figure 7 shows an external view of the test specimen after the failure property confirmation test. Radial cracking was found on the surface of the concrete block, but the integrity of other parts was maintained.

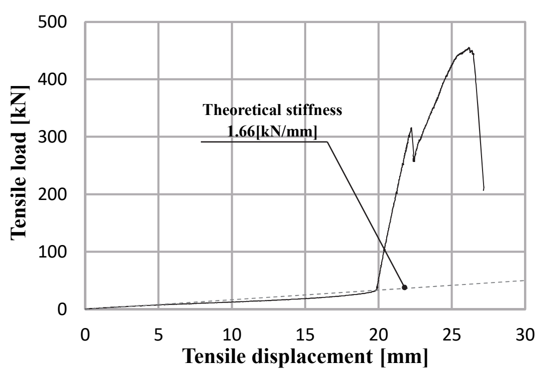


Figure 6. Results of the failure property confirmation tests.

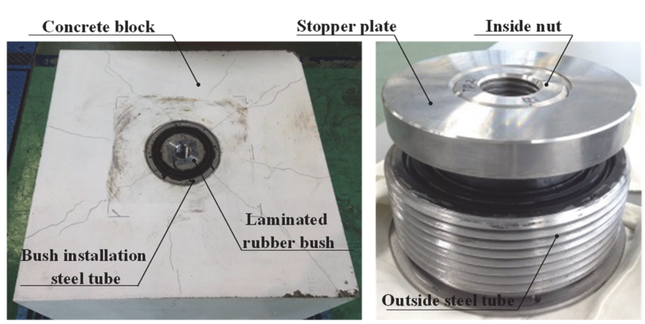


Figure 7. Condition of test specimen (After failure property confirmation test).

OUTLINE OF SYSTEM TESTS. Various performance confirmation tests were carried out using test specimens in which the TOS System was installed on full-size seismic isolator (system test specimens), in order to confirm the effect on the horizontal stiffness of the seismic isolator due to using the TOS System, and the vertical movement when a tensile force was acting. The test specimens consisted of square natural rubber type seismic isolator with an upper flange joined to a concrete block with 8 No. laminated rubber bushes installed uniformly on the same circumference (Figures 8, 9). Note that the specification of the laminated rubber bushes was the same as the specification for those used in the element tests.
Table 1 shows the loading method and loading conditions. In order to confirm the performance in the vertical direction, vertical loading tests, vertical tensile tests, and shear tensile tests were carried out, and in order to confirm the performance in the horizontal direction, horizontal shear tests and tensile shear tests were carried out. There were 2 horizontal loading directions, 0° direction and 45° direction. The maximum shear strain in each of the tests was set at 270% of the design criterion. Also, the maximum displacement in the vertical tests was 20 mm, at which there was contact between the outer ring of the laminated rubber bush and the stopper plate.

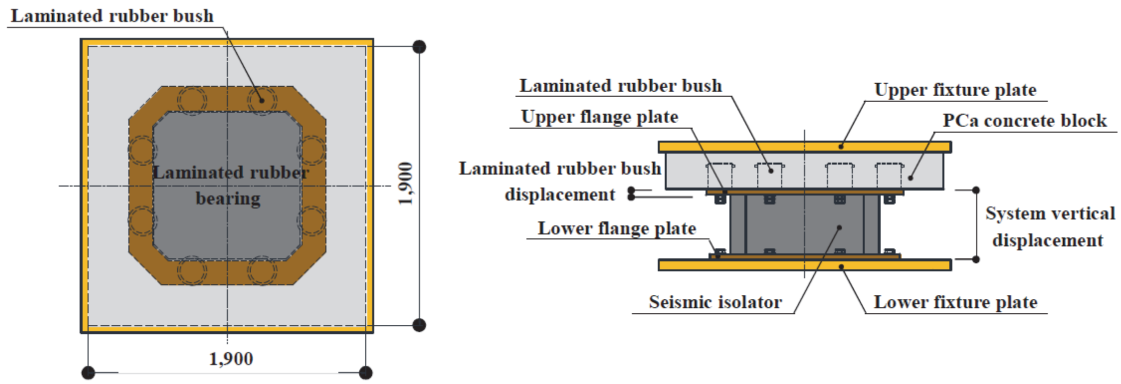
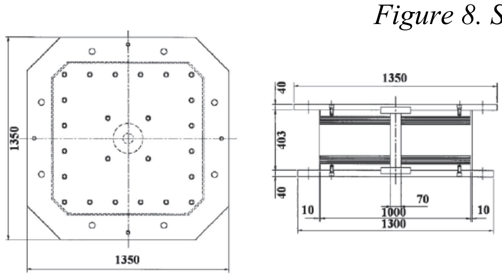


Figure 8. System test specimens.



Rubber elastic shear modulus	0.329 N/mm^2
Height of device	483.4 mm
Rubber external shape	1,000 x 1,000 mm
Rubber layers	7 mm×9 layers
Rubber effective cross-sectional area	976,152 mm^2
Internal steel plates	4.3 mm×28 No.
Connecting steel plates	40 mm×2 No.
Primary shape coefficient	35
Secondary shape coefficient	4.9

Figure 9. Parameters of natural rubber type seismic isolator.p

Table 1. Test Outline (loading method and loading conditions)

Test name	Vertical loading test	Vertical tensile test	Shear tensile test	Horizontal shear test	Tensile shear test
Loading method	Fv: Fluctuating load	δv: Unidirectional displacement	Fv: Constant load δh: Constant displacement δv: Unidirectional displacement	Fv: Constant load δh: Horizontal displacement	δv: Constant displacement δh: Horizontal displacement
Evaluation items	• Laminated rubber vertical stiffness (basic property)	• Rubber bush movement in the vertical direction	• Movement of rubber bush during horizontal load application	• Laminated rubber horizontal stiffness (basic property) (strain dependence) (surface pressure dependence)	• Laminated rubber horizontal stiffness (strain dependence) • Rubber bush horizontal direction movement
Loading direction	-	0°, 45°	0°, 45°	0°, 45°	0°, 45°
Loading conditions	σ=15±4.5 [MPa]	δv=0～20 [mm]	δv=0～20 [mm] γ=100,200,270 [%]	σ=0.15 [MPa] γ=100,200,270 [%]	δv=10 , 20 [mm] γ=100,200,270 [%]

The tensile stiffness of the system test specimens can be represented by the following equation as springs with the tensile stiffness of the seismic isolator and the laminated rubber bush in series.

$$\frac{1}{{}_tK_s}=\frac{1}{{}_tK_v}+\frac{1}{\sum {}_tK_b} \tag{3}$$

${}_tK_s$: System test specimen tensile stiffness, ${}_tK_v$: Seismic isolator tensile stiffness
${}_tK_b$: Laminated rubber bush tensile stiffness , ${}_cK_v$: Seismic isolator compressive stiffness

$${}_tK_v=0.05\cdot{}_cK_v$$

SYSTEM TEST RESULTS (PROPERTIES IN THE VERTICAL DIRECTION). Figure 10 shows the results of the vertical loading tests and the results of the vertical tensile tests. The tensile stiffness of the system overall was greatly reduced, so the effectiveness of the TOS System is confirmed.

From the tensile load - tensile displacement relationship for the laminated rubber bush on its own in the tensile test and the system overall, it can be seen that the system overall move smoothly with respect to tensile loads, and in the range up to a vertical displacement of 16 mm, the tensile stiffness of the system as a whole is in general agreement with the theoretical value.

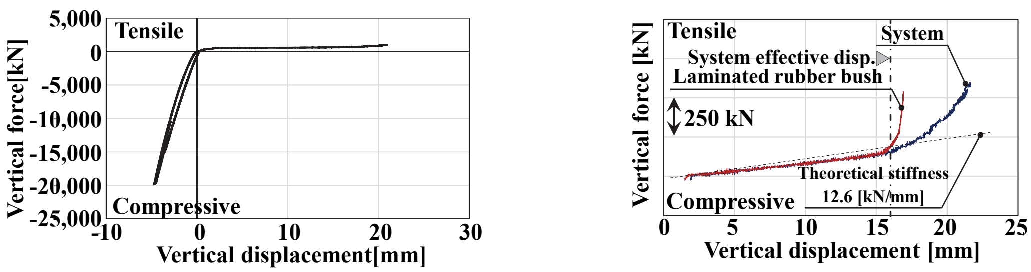
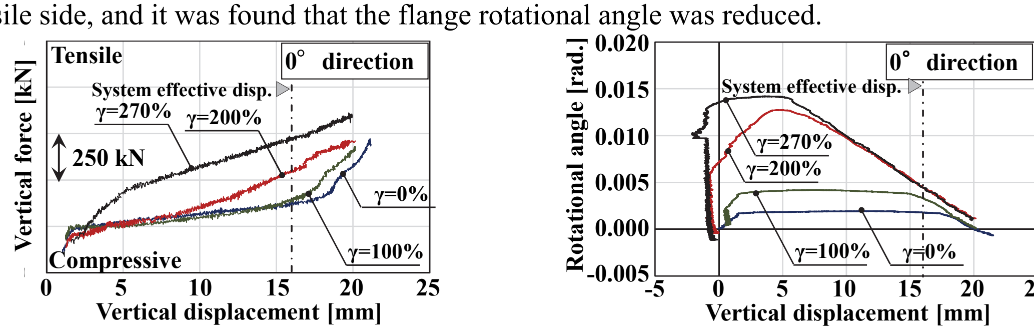


Figure 10. Vertical loading tests and vertical tensile test results.

Figure 11 shows the tensile load - tensile displacement relationship in the shear tensile tests. During shear tensile testing, the greater the shear deformation the sooner the laminated rubber bush acted on the stopper plate and the system stiffness increased, so compared with a simple tensile test (γ = 0%) the tensile stiffness was greatly increased.

From the tensile displacement and flange rotational angle relationship, the reason a flange rotational angle was generated at a vertical displacement of 0 mm is because horizontal shear deformation was applied first as the loading procedure. The greater the horizontal shear deformation, the greater the tensile displacement of the laminated rubber bush on the tensile side, and the sooner the flange rotational angle increased. When tensile displacement was applied, the laminated rubber bush acted on the stopper plate on the tensile side, and it was found that the flange rotational angle was reduced.



(a)load – displacement relationship (b)Flange rotational angle – displacement relationship

Figure 11. Shear tensile test results.

SYSTEM TEST RESULTS (HORIZONTAL PROPERTIES). Figure 12 shows the horizontal hysteresis curve at a shear strain of 100% for a surface pressure of 15 [N/mm2]. Comparing the cases where the seismic isolator was fixed with bolts (without TOS System) and the case where it was fixed with the laminated rubber bush (with TOS System), it can be seen that there is no major difference in the hysteresis curves for the two results. From this it can be confirmed that there is no effect on the seismic isolator shear stiffness due to fixing with the laminated rubber bush.

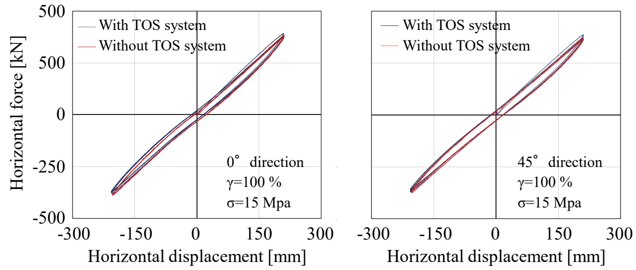


Figure 12. Comparison of cases with and without TOS System.

Figure 13 shows the horizontal hysteresis curves in the shear test at tensile displacements of 10 and 20 mm and surface pressure of 15 and 0 [N/mm2], and Figure 14 show the shear stiffnesses at each shear strain. Note that the shear stiffnesses shown here were calculated from the horizontal hysteresis curves of the 3rd cycle of the shear tests.

There were differences in the shear stiffness at tensile displacements of 10 and 20 mm for surface pressures of 15 [N/mm2] and 0 [N/mm2] due to surface pressure dependence. However the results showed that the shear stiffnesses under the strain conditions of tensile displacements 10 and 20 mm and surface pressure 0 [N/mm2] were virtually the same. Therefore it is considered that the evaluation of the shear stiffness of the seismic isolator when the TOS System is provided can be taken to be the same as for the normal installation method.

Figure 15 show the horizontal shear deformation and flange rotational angle relationship for the tensile shear tests at a shear strain of 200%. The flange rotational angle was greatest at a tensile displacement of 10 mm, with a maximum value of about 0.01 rad., from which it can be seen that excessive rotational deformation was not produced.

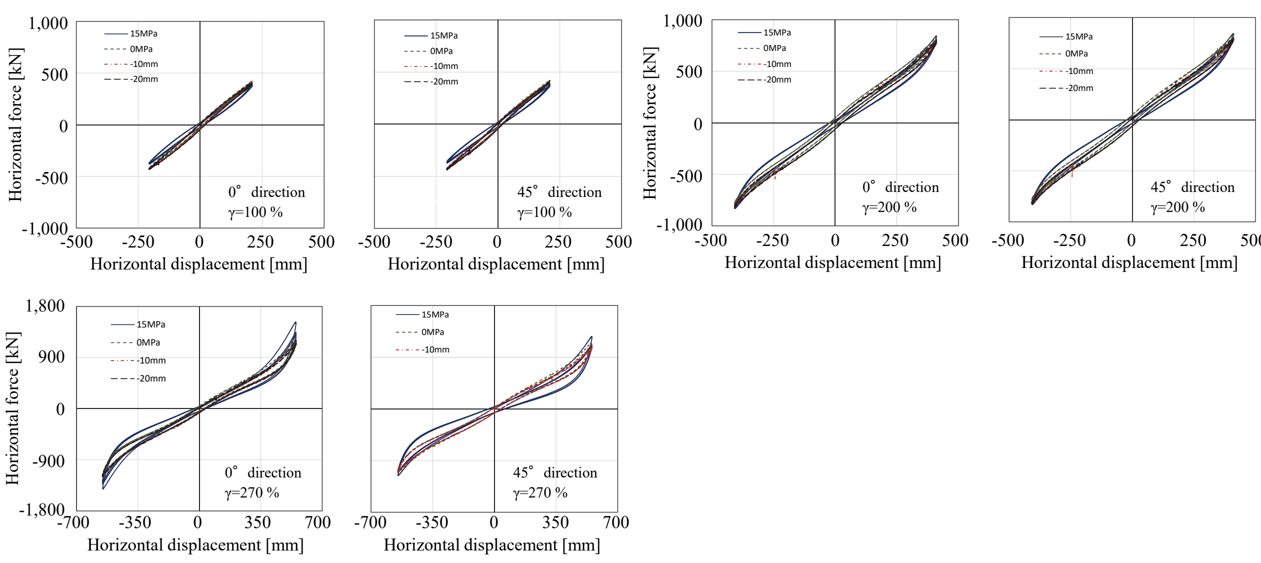


Figure 13. Load - horizontal displacement relationship.

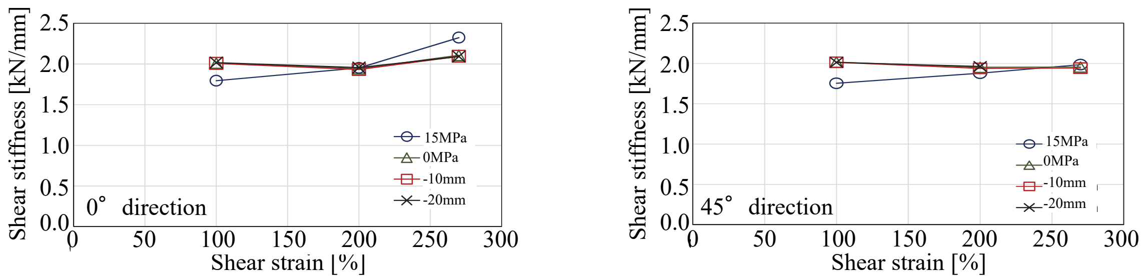


Figure 14. Shear stiffness of seismic isolator.

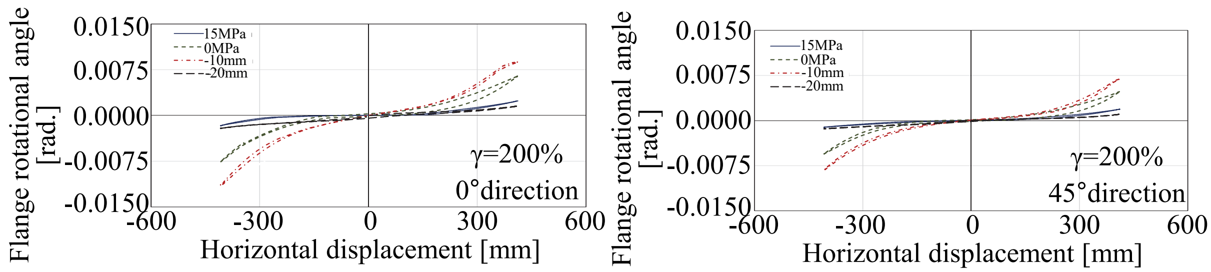
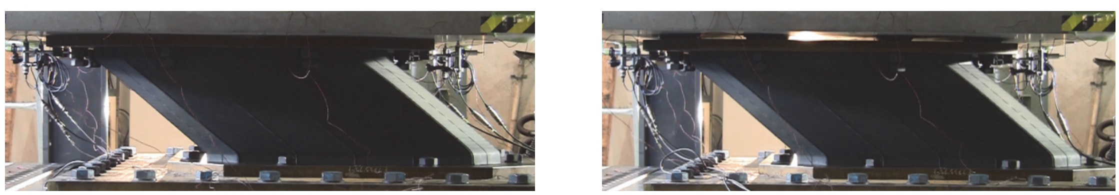


Figure 15. Flange rotational angle.



(a) Surface pressure 15 [N/mm2] (b) Tensile displacement 20 mm

Figure 16. Tensile shear test (0° direction, γ = 200%).

CONCLUSION

This paper as describes in outlined the newly developed TOS System, a method for dealing with uplift in seismic isolation. From the results of various tests, the following knowledge was obtained.

1) It was confirmed that the laminated rubber bush moves smoothly under tensile deformation.
2) The theoretical value of the tensile stiffness was generally accurately evaluated for both the laminated rubber bush on its own and the overall TOS System.
3) It was confirmed that the horizontal properties of the seismic isolator when provided with the TOS System are virtually the same as for the normal installation method.
4) It was confirmed that the effect on the horizontal properties of the seismic isolator is small when tensile displacement is generated in the TOS System.

References

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