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DEVELOPMENT OF EVALUATION METHOD FOR SEISMIC ISOLATION SYSTEMS OF NUCLEAR POWER FACILITIES - BREAK TEST OF FULL-SCALE LEAD RUBBER BEARINGS FOR NUCLEAR FACILITIES, PART 2 ULTIMATE PROPERTIES OF LRB BASED ON BREAK TESTS -

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ABSTRACT

To investigate the ultimate properties of lead rubber bearings (LRB), which were designed for applying base-isolated nuclear power plants (NPPs), static shear break tests and tensile break tests were conducted for full-scale LRB with 1600 mm in diameter and for its half-scale LRB. A horizontal load was applied up to the shear break point with several constant axial loads in the shear break test. A tensile load was applied up to the tensile break point with and without offset shear deformations in the tensile break test. This paper presents the load-deformation relationship of the LRB obtained in the break tests. Based on the test results, horizontal and tensional linear limits of the LRB were evaluated to contribute to the design of base-isolated NPPs. In addition, the validity of the hardening stiffness model of the LRB, which was used for earthquake response analysis, was examined by comparing the model to the test results. Finally, the results of the friction tests conducted after the break tests using broken LRB specimens are shown.
Horizontal hysteresis curves for three identical full-scale LRB specimens under the design compressive stress showed almost the same curves up to the shear break and the obtained shear-breaking strains were around 450%, which indicate small variations in the horizontal properties of the LRB under the same load condition. Tensile-breaking strains decreased with an increase in the offset shear deformations in the tensile break tests. The evaluated horizontal linear limit of strain was between 274% and 302%, and tensional linear limit of stress was between 1.0 MPa and 1.4 MPa.

INTRODUCTION

By applying the seismic isolation system to NPPs, seismic loads can be reduced both for reactor buildings and for inner equipment. Furthermore, the seismic isolation system increases the seismic safety margin. Evaluation of the residual risks against beyond design earthquakes is required in the seismic design of NPPs in Japanese regulation. For those circumstances, the national project called “Development of evaluation method for seismic isolation systems of nuclear power facilities” has been carried out by Sato et al. (2014). As a part of the project, break tests for full-scale LRB with 1600 mm in diameter designed for base-isolated NPPs were carried out to investigate the ultimate properties of the LRB, by Kosugi et al (2014). The specifications of the LRB were determined to satisfy the required response limitations through earthquake response analyses of base-isolated NPPs subjected to the design earthquakes by Asano et al. (2014). The main feature of the LRB is that the cross-sectional area of the lead plug in the LRB is about one and a half times larger than that of the LRB in the market to increase damping. Because of the large cross-sectional area of the lead plug, two types of lead plug were used for the specimens. One type is the single-plug type, where one thick lead plug is placed at the center of the specimens. The other type is the multi-plug type, where four slim plugs are placed in the specimens. The total cross-sectional area of the plug is the same for both types. The rubber material used for the LRB specimens is called the G4 type, which have the elastic shear coefficient as of G = 0.385 MPa at 20 degrees centigrade. The G4 rubber is popular for seismic rubber isolators in Japan. Detailed specifications of the LRB specimens used for the break test and the test cases are described in part 1 of the series of papers on this conference.

RESULTS FOR THE BREAK TEST

Shear Break Tests

For the shear break tests, the monotonous horizontal load was applied up to the break under several constant axial loads after applying two cyclic shear strains at 100%. The constant axial load was set as an axial stress of 1 MPa, 0 MPa, -5 MPa, -8 MPa, -15 MPa, and -30 MPa, where negative values indicate compressive stress. The design stress for dead load is -5 MPa. The range of applied axial stresses was defined based on the earthquake analyses for assumed base-isolated NPPs, where the level of input earthquakes was increased up to the break of the LRB. Because of the axial load capacity limitations for the test machine, half-scale LRB were used for the constant stress of -15 MPa and -30 MPa. To investigate variations on the load-displacement relations of the LRB, three identical full-scale specimens of the single-plug type, and two full-scale specimens of the four-plug type were tested under the design compressive stress of -5 MPa.

Figure 1 shows the typical deformation of the LRB specimens in the shear break test. Each laminated rubber layer of the LRB deformed uniformly in shear up to the break. Shear break began at the lower left or upper right portion of specimens. Through the specific observations for the ruptured surface of specimens after the break tests, it was found that the portion where the shear break started was rubber, not the boundary surface between an inner steel plate and a rubber.


(a) Just before break (460% shear strain)

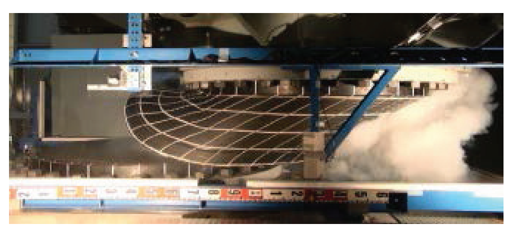
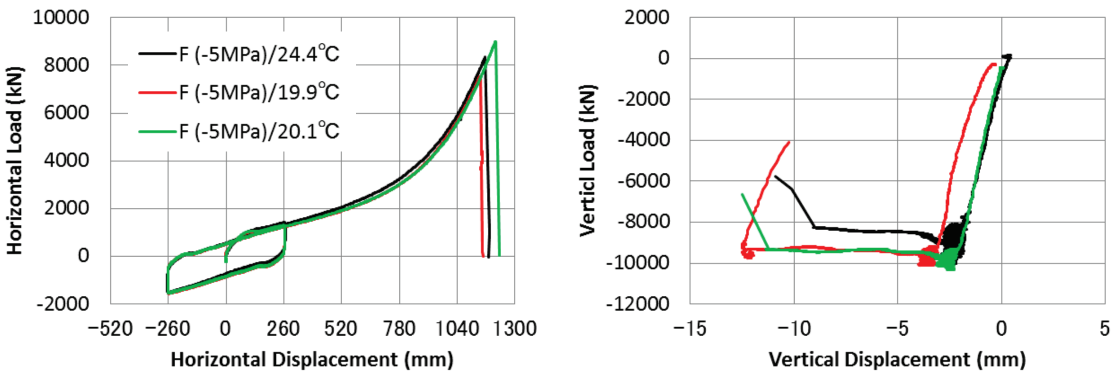

(b) Just after break

Figure 1. Typical deformation of the LRB in the shear break test

Figure 2(a) shows horizontal load - displacement relations for three identical full-scale LRB with single-plug type tested under the design stress of -5 MPa. The scale interval of 260 mm in the horizontal displacement axis coincides with 100% shear strain interval. The temperature at rubber surface of the specimens measured before the break tests are indicated in the legend on the figure. It is found that each hysteresis curve is almost the same up to shear break, and a horizontal displacement at shear break is between 1142 mm and 1211 mm that correspond to 439% and 466% shear strains, respectively. Shear breaking strains for the full-scale specimens under the compressive loads were exceeded an intended allowable breaking strain of 400%. Figure 2(b) shows vertical load - displacement relations. Vertical displacements were about -3 mm when the initial compressive stress of -5 MPa was applied before horizontal loadings. Along with the increase in horizontal displacement, the vertical displacement also increased and came to about -9 mm to -12 mm until shear break.

Figure 3 shows the test results for two full-scale LRB with the four-plug type compared with the test result for LRB with single-plug type in Figure 2. Among two specimens with the four-plug type, a different horizontal load direction was set with each other taking into account of the layout of four plugs. A test case in which horizontal load was applied along a diagonal direction in the four-plug layout is denoted “45 deg” in the figure. Horizontal loads are slightly different each other during cyclic 260 mm loading because of different temperatures. Within 650 mm (250% shear strains) horizontal displacement, load - displacement relations are similar with each other. Over 650 mm, however, trends in increase of horizontal loads are different among the LRB with four-plug type. The horizontal loads for the four-plug type are some larger and smaller than that for the single-plug type over 650 mm. However, an average property of the two LRB with four-plug type seems to be the same as the LRB with the single-plug type. Shear braking strains for the two LRB with four-plug type are 437% and 454%, which are almost the same for the LRB with single-plug type.



(a) Horizontal direction (b) Vertical direction

Figure 2. Load and displacement relations for identical full-scale LRB with the single-plug type

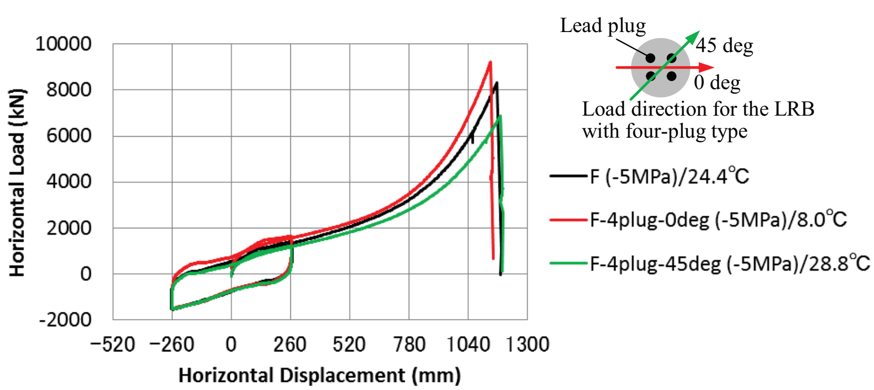


Figure 3. Horizontal load and displacement relations for LRB with the four-plug and single-plug type

Figure 4 shows shear stress - shear strain relations for full-scale and half-scale LRB specimens under the several constant axial stresses. Full-scale and half-scale specimens are marked “F” and “H”, respectively in the figure. The shear stresses are calculated from horizontal loads divided by the whole sectional area of the LRB specimen including rubber and lead plug. Considering that the yield stress of lead plugs are influenced by the temperature, hysteresis curves within about 250% shear strains seem to be similar to full-scale and half-scale LRB. Over 250% shear strains, however, hardening properties seem to be different between full-scale and half-scale specimens. Shear breaking stresses for half-scale LRB are higher than that for full-scale specimens. Effects of temperature on the hardening property are unclear now and needs further study.

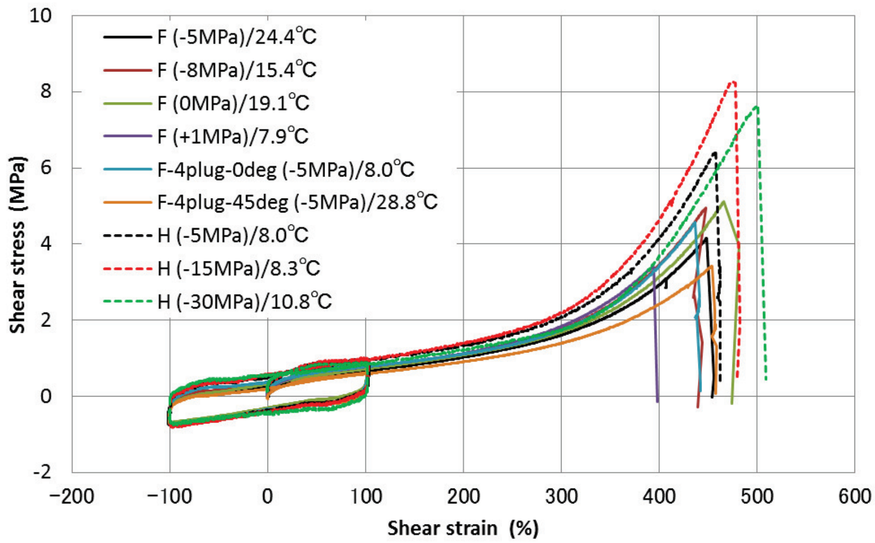


Figure 4. Shear stress and shear strain relations for full-scale and half-scale LRB

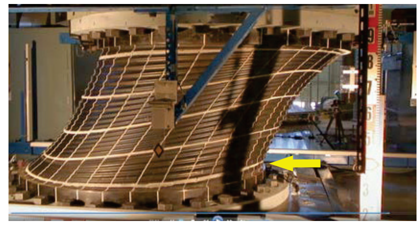
Tensile Break Tests

Tensile break tests were conducted under several initial offset shear strains for full-scale LRB. The offset shear strains were set at 0%, 100%, 200%, 300%, and 400%, in which the 0% offset corresponds to a simple tensile test. The loading pattern for the tensile break tests was as follows. The design compressive stress of -5 MPa was loaded first, and next horizontal displacement was applied to reach the given offset shear strains, and then vertical displacement toward a tensile direction was applied until the tensile break. For the test case with offset shear strain of 200%, 300%, and 400%, two specimens were used, respectively, to see the repeatability of tensile break strains.

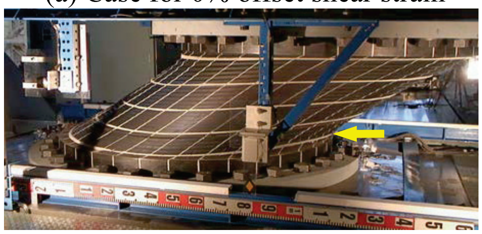
Figure 5 shows deformations for LRB just before tensile break for the test case of 0%, 200%, 300%, and 400% offset shear strains. The portion where tensile break started is marked with a yellow arrow in the figure. In the case of the pure tensile break test (0% offset shear strain), each rubber layer deformed uniformly in tension. In the case of the test with offset shear strains, however, tensile deformations concentrated at the edge of rubber within an area where uppermost and lowermost rubber layers were overlapped. The concentrated tensile deformations were clearly seen in the case for 200% offset.

Figure 6 and Figure 7 show vertical and horizontal load - displacement relations of the LRB with single-plug type, respectively. Positive values indicate in tension for the vertical hysteresis curves in figure 6. The tensile breaking strain was 291% (757 mm vertical displacement) for the case of 0% offset shear strain. For the case of offset shear strains, the tensile break strains were smaller due to the increase in the offset strains. It should be noted that a tensile load was applied two times to check the test equipment for the case of 100% offset, where the vertical displacement reaches around 45 mm for the first load. Horizontal hysteresis curves shown in figure 7 were similar with each other when the temperatures of specimens were similar.

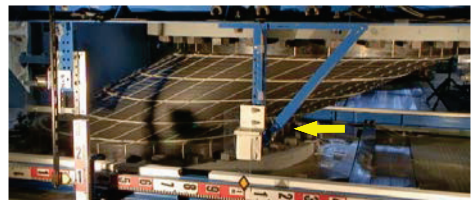
(a) Case for 0% offset shear strain



(b) Case for 200% offset shear strains

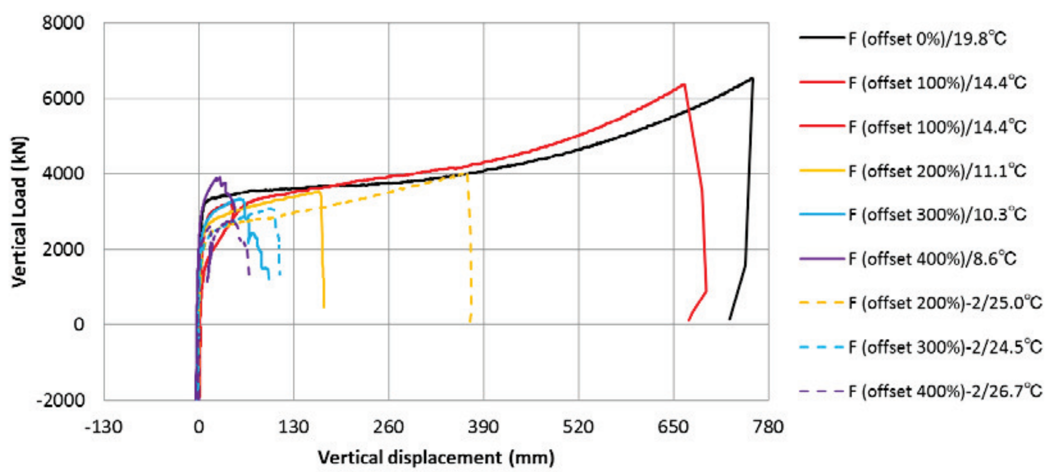


(c) Case for 300% offset shear strains

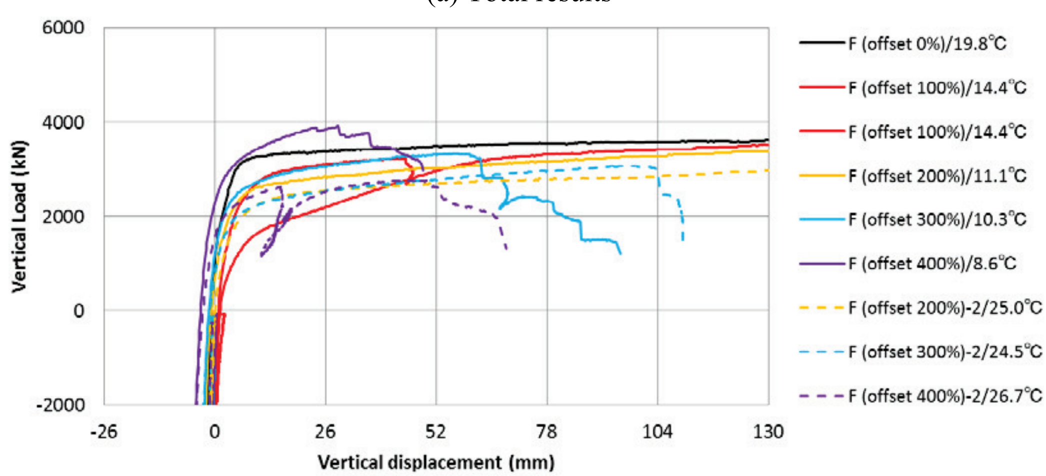


(d) Case for 400% offset shear strains

Figure 5. Deformations for full-scale LRB just before tensile break



(a) Total results



(b) Enlarged view for (a)

Figure 6. Vertical load and displacement relations of the tensile break teste for full-scale LRB

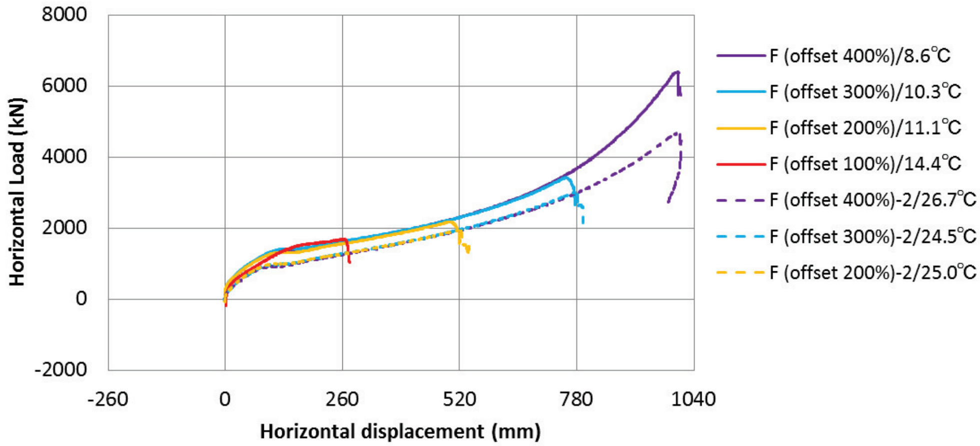


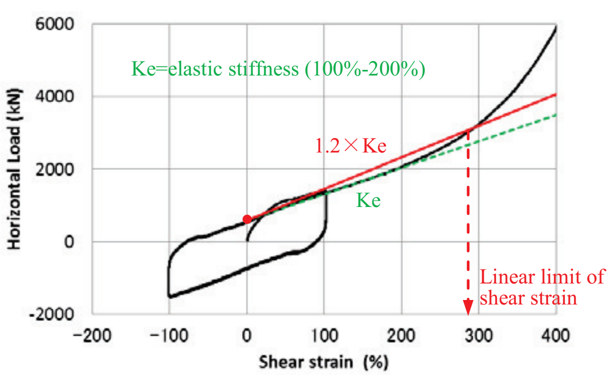
Figure 7. Horizontal load and displacement relations of the tensile break teste for full-scale LRB

EVALUATION FOR LINEAR LIMIT OF LRB BASED ON THE BREAK TEST

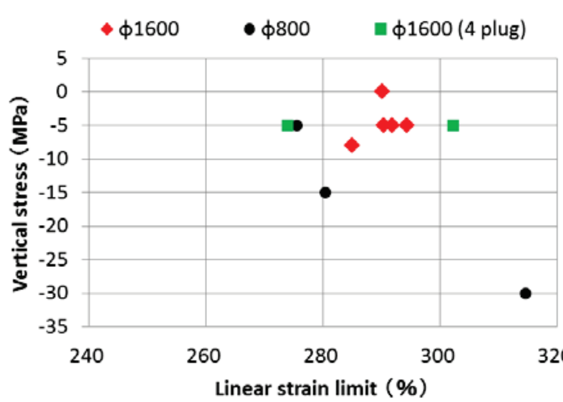
Linear Limit of Shear Strain

Linear limit of shear strains were evaluated based on the results for the shear break test. Figure 8(a) shows the evaluation procedure following JEAG 4614-2013 (2013). The evaluation method is as follows. First, plot a straight line that fits with the elastic stiffness in the range from 100% to 200% shear strain. Next, draw a second straight line with a gradient of 1.2 times larger than that for the first plotted line, where the horizontal load at 0% shear strain on those two straight lines is coincident. A shear strain at an intersection point of the hysteresis and the second straight line is defined as the linear limit of shear strain.

Figure 8(b) shows the relationship between the evaluated linear limit of shear strains and vertical stresses applied to as the constant axial load for full-scale ϕ1600 and half-scale ϕ800 specimens. The linear limit of shear strains for full-scale specimens are between 274% and 302%, where vertical stresses are within 0 MPa to -8 MPa. The linear limit of shear strains for half-scale specimens under the vertical stress of -5 MPa to -15 MPa are almost the same as that for the full-scale LRB. Under the high compressive stress of -30 MPa for the half-scale specimen, a somewhat large linear limit of shear strain of 315% was observed. It is confirmed that the full-scale LRB of G4 rubber has a linear limit of shear strains over 250%.



(a) Evaluation procedure



(b) Evaluated linear limit of shear strain

Figure 8. Evaluation for linear limit of shear strain based on the shear break tests

Linear Limit of Tensile Stress

Linear limit of tensile stresses were evaluated based on the tensile break test results following the evaluation method defined in JEAG 4614-2013. The evaluation procedure for the linear limit of tensile stress shown in figure 9 is as follows. First, plot a straight line that connects a tensile stress equivalent to the shear stiffness of rubber G (G = 0.39 MPa for G4 type rubber) and the origin on the tensile stress - tensile strain relationship for the LRB. Next, shift the straight line towered a 1% tensile strain remains. A tensile stress at the crossing point of the shifted straight line and the tensile hysteresis curve is defined as the linear limit of tensile stress.

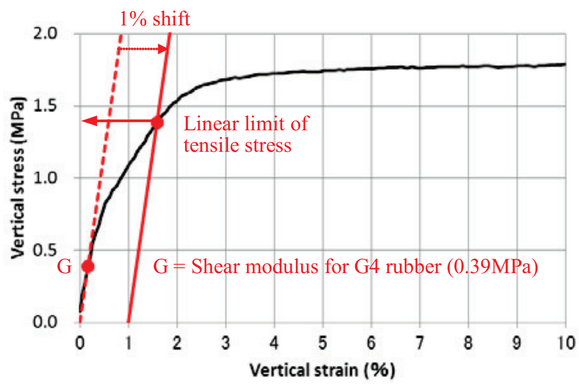


Figure 9. Evaluation procedure for linear limit of tensile stress

Figure 10 shows vertical stress - vertical strain relationships at the small strain region for a full-scale LRB with and without offset shear strain. A positive value for the vertical stress and vertical strain is in tension. Those vertical stresses were calculated by using vertical loads and the sectional area of the rubber part of the LRB specimens. In figure 10, adjusted hysteresis curves are presented so that all the hysteresis curves pass through the origin of the axis. Those adjusted hysteresis curves are obtained just by shifting the vertical strain of the original hysteresis curves. It is found that the vertical stresses of hysteresis curves obtained under offset shear strains are lower than that for 0% offset shear strain, except the test case of 400% offset shear of the first specimen. There is a possibility that the combination of the low temperature of 8.6℃ and the large initial offset shear strain of 400% affected the tensile property for the first specimen with 400% offset.

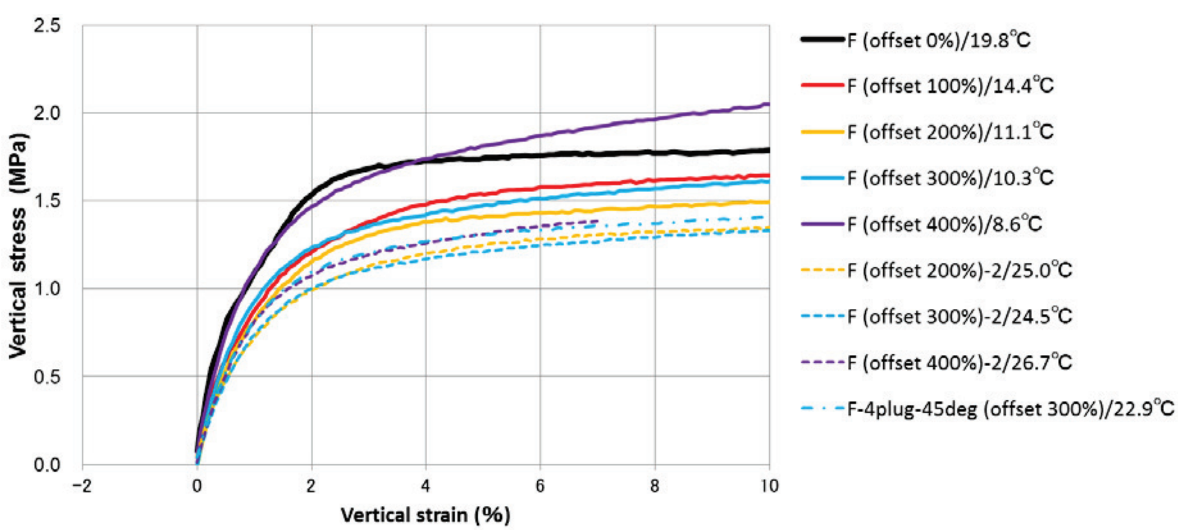


Figure 10. Vertical stress and vertical strain relations at the small strain region for full-scale LRB

Figure 11 shows the relationship between the evaluated linear limit of tensile stresses and offset shear strains. The linear limits of tensile stresses are in the range from 1.0 MPa to 1.4 MPa. Within the offset shear strains up to 200%, which correspond to the region for liner limit of shear strains, the linear limit of tensile stresses are decreased linearly with an increase in the offset shear strains.

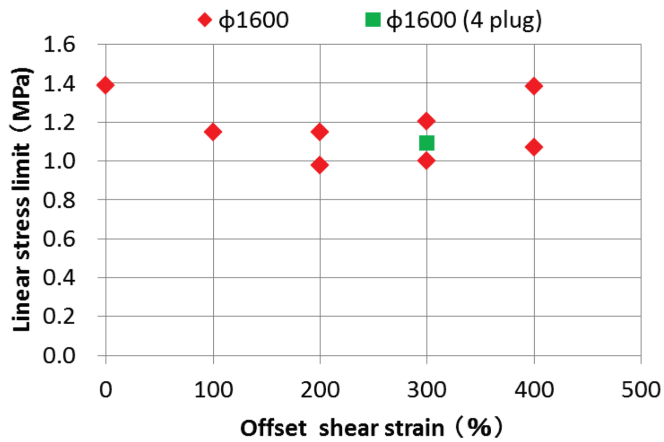


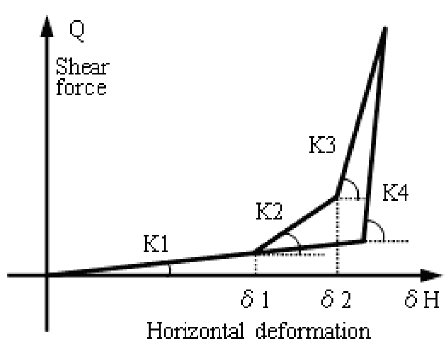
Figure 11. Relationship between evaluated linear limit of tensile stresses and offset shear strains

CONFIRMATION ON VALIDITY OF HARDENING STIFFNESS MODEL FOR LRB

By comparing the shear break test results and the hardening stiffness model for the LRB, the validity of the model was examined. The hardening stiffness model is used in earthquake response analyses far beyond the design level to evaluate residual risks.

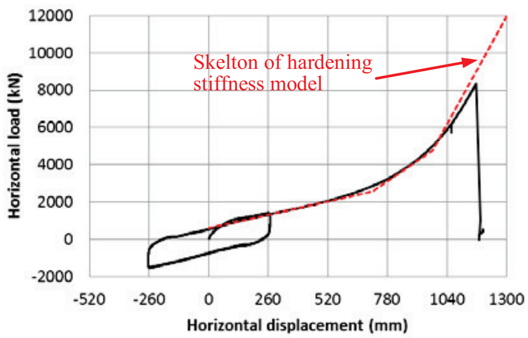
Figure 12 shows the hardening stiffness model for LRB of G4 rubber. In figure 12, a hysteresis for the rubber part of LRB is shown. The hardening model was developed based on test results by using small LRB specimens.

Figure 13 shows horizontal hysteresis curves for full-scale LRB under the initial compressive stress of -5 MPa, -8 MPa, and 0 MPa compared with the skeleton curve of hardening stiffness model. The stiffness among displacement from 260 mm to 520 mm (100% to 200% shear strains) for the test fits the elastic stiffness K1 of the hardening stiffness model. The skeleton curve of the model agreed well with the test results, and it is confirmed the validity of the model by full-scale LRB specimens.

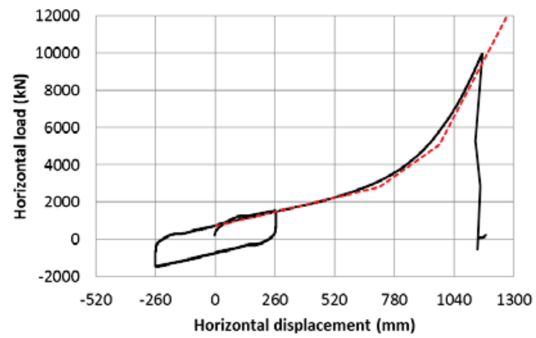


Hardening Stiffness Model (G4 rubber)
K1 = Elastic stiffness for rubber of LRB
K2 = 3 × K1
K3 = 8 × K1
K4 = 20 × K1
δ1 = 275%
δ2 = 375%

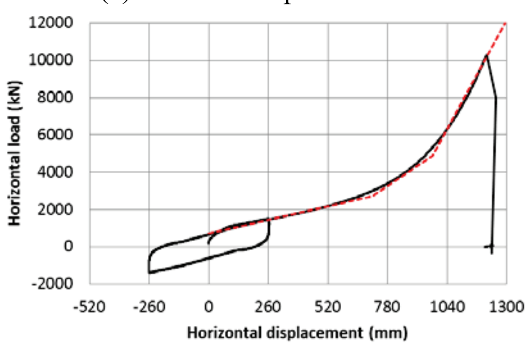
Figure 12. Hardening stiffness model for the rubber part of the LRB



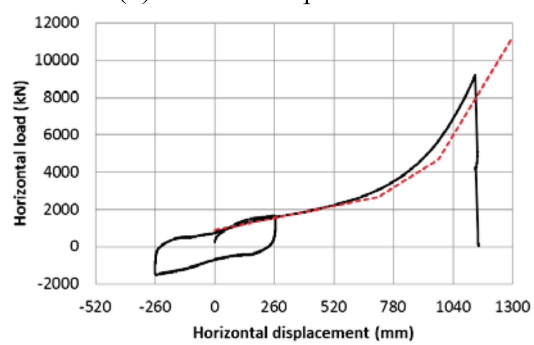
(a) -5 MPa compressive stress



(b) -8 MPa compressive stress



(c) 0 MPa compressive stress



(d) -5 MPa compressive stress (four-plug type)

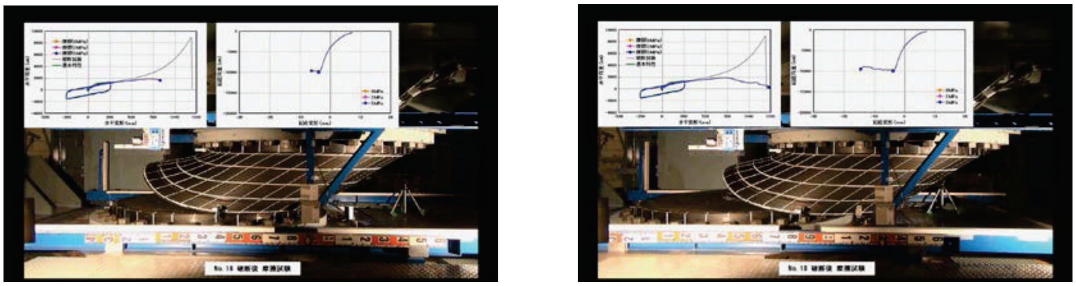
Figure 13. Comparison of the hysteresis curves for full-scale LRB with the hardening stiffness model

FRICTION TESTS BY USING BROKEN SPECIMENS AFTER THE BREAK TEST

Soon after the end of some break tests, friction tests were conducted to investigate characteristics for the broken LRB specimens to utilize in developing a mechanical model of broken LRB for the residual risk evaluation. In this paper, one of the friction tests carried out after the shear break test for full-scale LRB with a single plug is presented. Procedures for the friction test were as follows. First, a separated upper and lower part of the broken specimen was set at the normal position and a constant compressive load of -5 MPa was applied. Second, one cycle of 260 mm (100% shear strain) and a half cycle of 1300 mm horizontal displacement was applied. Same steps were repeated for the constant compressive load of -2 MPa and -8 MPa, respectively.

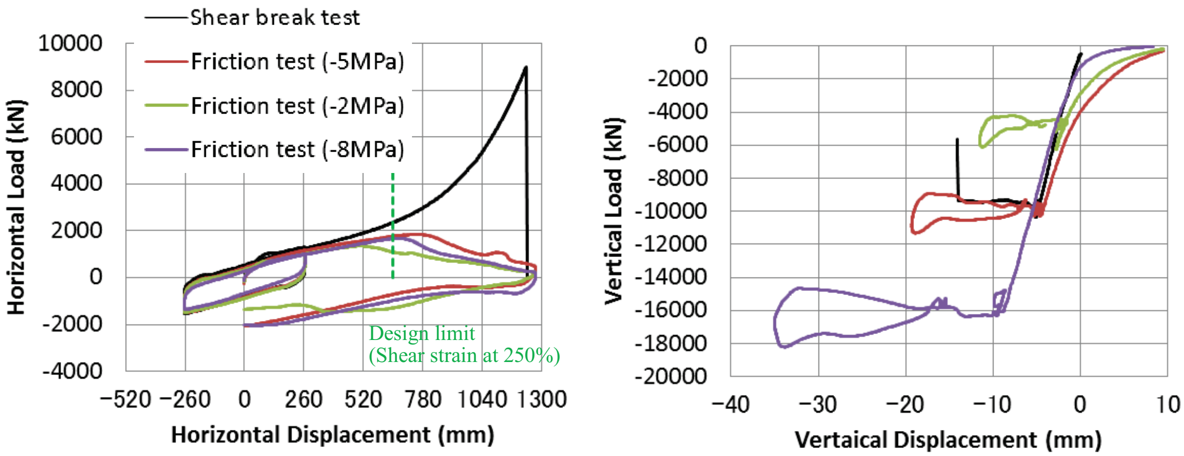
Figure 14 shows deformations of the specimen when a slide started and the horizontal displacement reached at 1300 mm under the -5 MPa compressions. No sliding was observed during the one cycle of 260 mm loading, and the slide begun at around 780 mm on the way to the 1300 mm. At 1300 mm displacement, the edge of fractured surface for the upper part of broken specimen was located outside of the lower flange, but the fractured surface did not contact the platform of the test machine.

Figure 15 shows hysteresis curves for horizontal and vertical directions together with shear break test results. The horizontal hysteresis for the friction test during one cycle of 260 mm is similar to the one for the shear break test. A slid began at around 520 mm to 780 mm depend on the compressive stress, and while the specimen was sliding, horizontal load was gradually decreased with increasing horizontal displacement. From the vertical hysteresis, the broken specimen holds almost constant compressive load without excessive vertical displacement. This indicates that supporting abilities of the LRB remains even after the break.



(a) The moment at slide started (b) Horizontal displacement at 1300 mm

Figure 14. Deformation for full-scale LRB during the friction test (Case for -5 MPa compression)



(a) Horizontal direction (b) Vertical direction

Figure 15. Hysteresis curves for friction test and shear break test

CONCLUSION

Shear break tests and tensile break tests for full-scale lead rubber bearings (LRB) with 1600 mm in diameter designed for postulated base-isolated NPPs were carried out to obtain shear and tensional properties up to break. Shear properties for three identical specimens under the design compressive stress showed good agreement with each other up to shear break. Influence of lead plug type on horizontal hysteresis curves was small. Evaluated linear limit of shear strains based on the shear break tests were from 274% to 302%, which exceeded 250% set out in the design. Evaluated linear limit of tensile stresses based on the tensile break test with and without offset shear strains were from 1.0 MPa to 1.4 MPa, which is almost the same as the allowable limit of tensile stress of 1.0 MPa in the design.

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