LARGE SCALE DYNAMIC FAILURE TESTS OF LOW DAMPING RUBBER BASE ISOLATORS

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SUMMARY

Two large scale dynamic tests were performed for different sized rubber base isolators that were both made of same low damping rubber with actual response velocity of seismic excitations. In each test a 220 ton mass was placed on four isolators located at the corners of the mass. The entire mass system was then placed on the large scale seismic simulator, which has dimensions of 15m by 14.5m, with a maximum velocity of 100cm/s, and a maximum displacement of 0.22m. The seismic simulator was used to drive the mass until the isolators reached failure. In the first the isolators of small second shape factor simply dropped down, but did not break. In the second test of large second shape factor however, all four isolators were completely sheared off.

INTRODUCTION

After Hyougoken Nanbu earthquake, many base isolated buildings have been constructed. For these building, the laminated rubber isolators have been used. The laminated rubber isolators are expected to have large horizontal displacement absorption and small horizontal stiffness. And moreover these basic characteristics, they also are expected to have a life of over 60 years. So many experimental studies have been curried out to ensure the dynamic ultimate strength for the load during great earthquake excitations. But almost all of these tests were conducted with small laminated rubber isolators because of the capacity limit of the shaking tables [2],[4]. Or the ultimate strength is pursued by a static experiment [1],[3]. Therefore the objective of our study is to observe the failure mode of the laminated rubber with actual velocity and to make a comparison between dynamic tests results and static tests results.

Figure 1 Base isolated structure model on a table

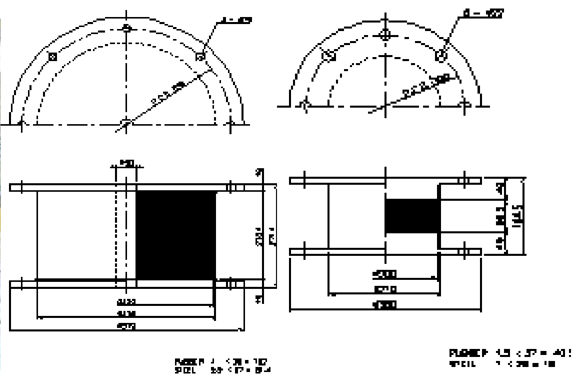

Figure 2 Two laminated rubber isolators for tests

DYNAMIC TEST MODEL

Figure 1 shows the base isolated structure model which was installed on the large scale earthquake simulator of National Institute of Earth Science and Disaster Prevention, which is the one horizontal direction shaking table.

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The structure was consisted of the mass of 200 ton which made of steel strips and the stage which made of H-shape steel frames. The stage has a mass of 20 ton, therefore the total mass on the four laminated rubber isolators is 220 ton. Each steel strips were combined by tension rods and stacked on the stage. Therefore, the mass could move as a rigid body. The dimensions of the mass were 7.0m by 4.9m and 5.5m high. Four laminated rubber isolators were used to support the mass with the natural period of 2 seconds. In these dynamic failure tests two different types of laminated rubber isolators which made of same natural rubber material were provided. For the safety two restraints were installed at both side of the mass with a gap between the mass and the restraint of 0.6m in the shaking direction. So the mass could not move over 0.6m in the shaking direction. The restraints were designed for absorbing the horizontal inertia force of the mass of 220 ton during seismic excitations. The restraints also have a gap in the vertical direction to support the mass after the buckling of the laminated rubber isolators. In this test, the gap in vertical direction was 0.045m.

LAMINATED RUBBER ISOLATORS

Figure 2 shows the laminated rubber isolators which were used in the dynamic failure tests. The both of laminated rubber isolators were made of mainly natural rubber of low damping (ξ = 2-3%). Two parameters, S1 and S2 for the shape of laminated rubber isolator, are defined as follows,

$$S_1 = \frac{d_r}{4 \cdot t_r}, S_2 = \frac{d_r}{n \cdot t_r}$$

dr: a diameter of laminated rubber isolator, tr : a thickness of single rubber layer, n: number of rubber layers. The slender shape isolators have a diameter of 0.42m, a single rubber layer thickness of 0.004m, a primary shape factor (S_1) of 26.25 , a second shape factor (S_2) of 2.76. The flat shape isolators have a diameter of 0.2m, a single rubber layer thickness of 0.0015m, a primary shape factor (S_1) of 33.3, a second shape factor (S_2) of 5.0.

The nominal pressure (vertical stress) are 3.528MPa for the slender shape isolators and 15.58MPa for flat shape isolators respectively. Both of the isolators have a same horizontal stiffness of 490kN/m. The predicted maximum horizontal displacements are also 0.42m for the slender shape isolator and 0.264m for the flat shape isolator respectively. Mechanical properties of natural rubber were as follows: Shear Modules G=0.6MPa, Hardness IRHD=40, Elongation ε =650%

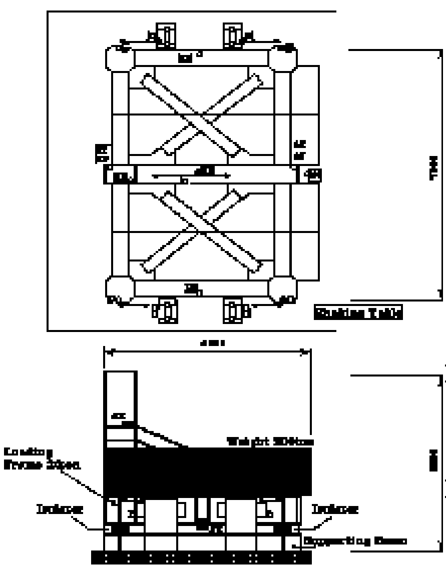


Figure 3 Outline of dynamic test model and Sensor distribution

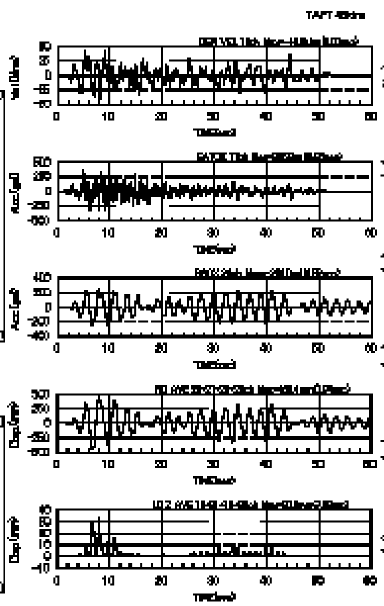


Figure 4 Time record of response of 45cm/s input

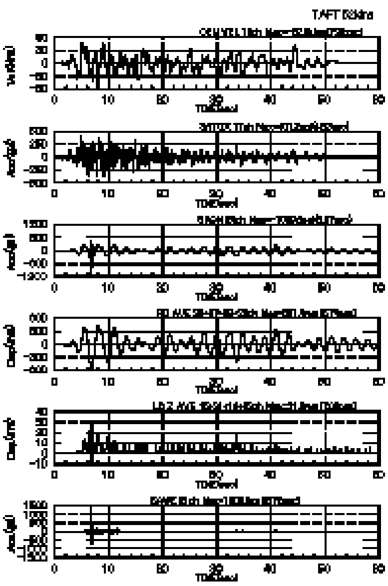


Figure 5 Time record of response of 52cm/s input

MEASUREMENT AND DYNAMIC TEST PROCEDURE

Figure 3 shows the position of the sensors. In this figure, AX, AY, AZ show the accelerators for X, Y, Z directions. And D shows the displacement transducers. Four vertical transducers at the each corners of the moving mass are used to measure the height reduction of the laminated rubber isolators. Five displacement transducers in X direction (shaking direction) are provided at the center and the each corners of the moving mass. Therefore the rotational, torsional and sway displacement could be measured. Acceleration, velocity and displacement of the shaking table were also measured. All data from the sensors were converted to digital data by the 12 bit analog-digital transducer with sampling time of 0.001sec. The restoring force F_H of the four rubber isolators is derived from the mass and the acceleration of the center of the gravity of the mass, or also given by using the dynamic pressure p_d of shaking table actuators , as follows:

$$F_H = m\,a, \qquad F_H = p_d\,A_c - m_t\,a_t$$

Where m is 220 ton of the moving mass, a is the response acceleration, A_c is actuator section area 2000 square cm, m_t is table mass 195ton, a_t is table acceleration.

In the dynamic failure test of the slender shape laminated rubber isolators, the artificial seismic wave which using Taft EW phase characteristics wave was used as the input ground motion. On the other hand, for the test of flat shape isolators, JMA Kobe waveform was used. In the shaking table tests, a suite of the wave forms with the different input velocity level were provided, because of the observations of basic characteristic of the laminated rubber isolator. Therefore, the laminated rubber isolators of slender shape were experienced 15 input earthquake motions of the different velocity level before the rubber isolator drop-down. The isolators of flat shape also experienced four input earthquake motions before the isolator shear-off.

DYNAMIC FAILURE TEST RESULTS

Slender shape laminated rubber isolator (S_2=2.76) Figure 4 shows the time record of response of the mass as input 45 cm/s of the artificial seismic wave which using Taft EW phase characteristics. In this figure, from the top to the bottom in turn, input velocity, input acceleration, response acceleration, horizontal displacement (relative displacement between the shaking table and the mass), and vertical displacement of the isolators are shown. The maximum acceleration of the mass was 250 gal, maximum total horizontal restoring force and horizontal displacement were 520kN and 0.45m. Horizontal displacement of 0.45m was 108% of the diameter of the laminated rubber isolator. Although there was no superposition areas of the laminated rubber isolator, the vertical bearing capability was not loosed. Maximum vertical displacement was 0.035m.At this input level, the mass did not dropped down. But as shown in Figure 6, the restoring force characteristic shows the negative slope over the horizontal displacement of 0.42m

Figure 5 also shows the time record of the response in case of the mass dropped down. In Figure 5, from the top to the bottom in turn, input velocity, input acceleration, response acceleration, horizontal displacement, and vertical displacement of the isolators and vertical acceleration of the mass are shown. The minimum input velocity was 52cm/s and the maximum displacement of the mass relative to the shaking table before failure was 0.534m. The isolators had displacement of 127% of their diameter and 351% of the rubber shear strain before they reached failure by buckling. In this case, when the mass dropped down, there were some shocks on the mass. At the moment of the drop-down, the response acceleration of 1308.9gal in the vertical direction was observed. On the other hand, the maximum horizontal acceleration was -1009.6gal. Both of

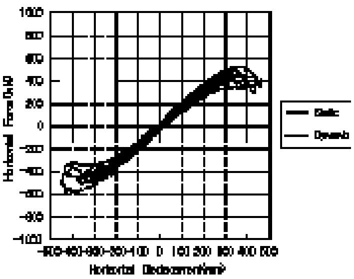


Figure 6 Restoring force curves of dynamic(45m/s) and static

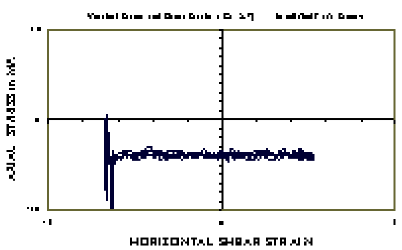


Figure 7 Relation between vertical stress and horizontal shear strain (52cm/s)

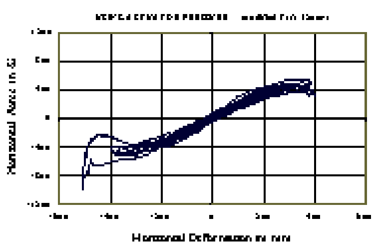


Figure 8 Restoring force curve of using actuator pressure(52cm/s)

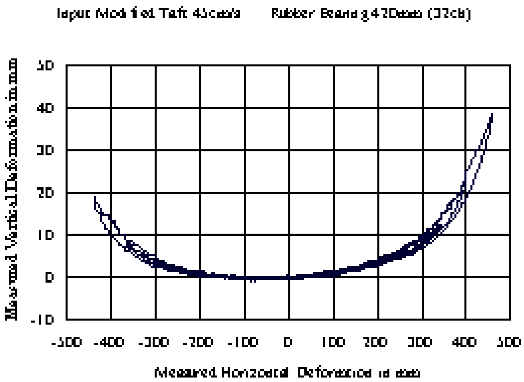
the acceleration wave form of vertical and horizontal direction looks like an impulse wave. In Figure 7, the relation of the vertical stress and horizontal shear strain is shown. Figure 8 shows the restoring force characteristics of using the dynamic pressures of shaking table actuators, which was not disturbed by the shock noise of the drop- down.

Figure9,10 shows the vertical displacement characteristics of an isolator and the averaged one of four isolators. Figure 9 shows the unbalanced vertical deformations. The unbalanced vertical displacements of isolators [5] was explained in the model of Figure 11. The vertical displacements ***v*** of isolators would vary with the changes of superposition area ***Si*** of rubber bearings, the overturning moments, and the horizontal shift ***u*** of gravity center of the mass which would be included in the overturning moment.

$$S_i = \frac{(d_r C_a(u))^2}{4}\cos^{-1}\left|\frac{u}{d_r C_a(u)}\right| - \left|\frac{u}{2}\right|\sqrt{(d_r C_a(u))^2 - u^2}\,, v = \frac{n \cdot t_r}{E_a S_i}\left[\frac{mg(L/2 \pm u) \mp maH}{L}\right]$$

where **Ea** is apparent elastic modulus of laminated rubber. In order to express the vertical displacements at large horizontal displacements ***u*** over ***dr***, ***Ca(u)*** *(=1+0.1* |***u***| in the calculation) was adopted. The calculated vertical displacements using the above equations are shown in Figure 11-15, neglecting static vertical displacement. Figure 11 shows the vertical displacements due to the overturning moments, Figure 12 is due to the gravity center shift. Figure 14 agrees with Figure 10. The agreement shows that the averaged vertical displacements of Figure 10 is given by the change of superposition area. Figure 15 shows fairly good agreement with Figure 9.

The deformation mode of the laminated rubber isolator at the drop-down is shown in Figure 16. After the drop-down, the mass was jumping up, so the mass continued to vibrate and was back to the original position. Although the isolators were experienced the buckling, there was no reduction of the restoring force characteristics and no damage in the laminated rubber isolators.



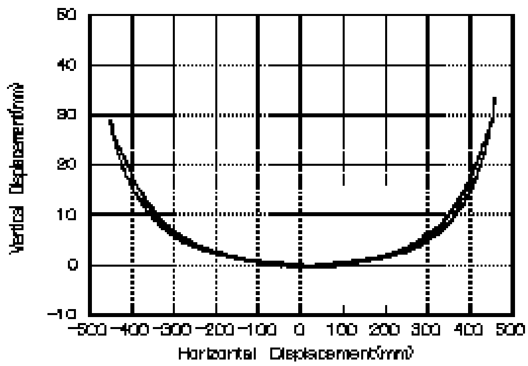
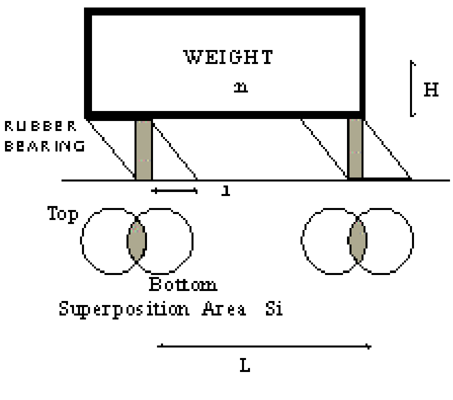
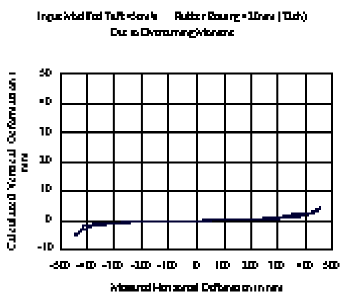


Figure 9 Relation of vertical and horizontal displacement one rubber bearing

Figure 10 Averaged relation of vertical and horizontal displacement of four rubber bearings





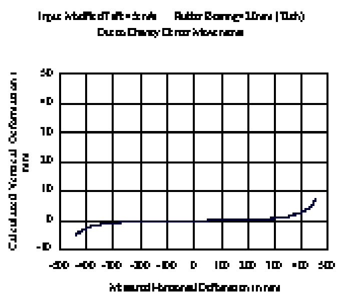


Figure 10 Model of vertical displacement analysis

Figure 11 Vertical displacement due to overturning moment

Figure 12 Vertical displacement due to gravity center shift

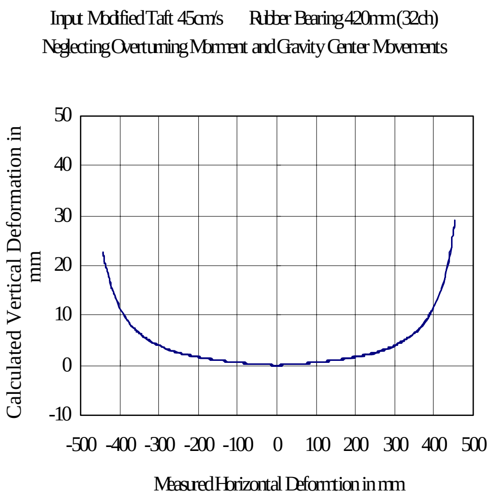


Figure 14 Vertical displacement without moment and gravity center movement

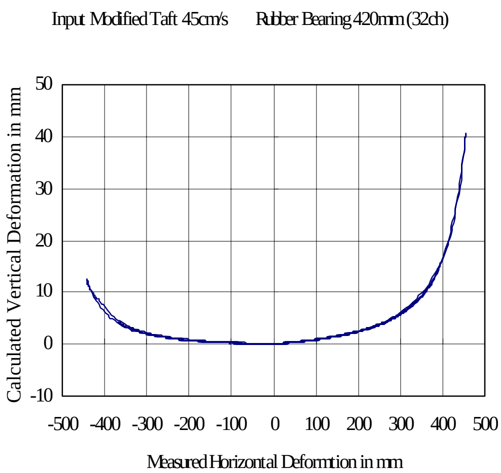


Figure 15 Vertical displacement including moment and gravity center movement

Figure 16 Deformation shape of slender rubber bearing

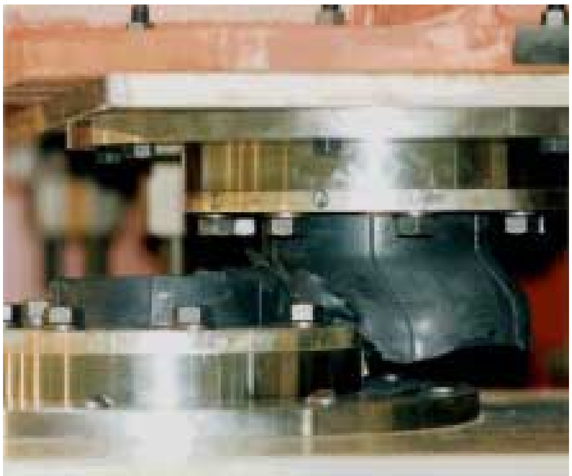


Figure 17 Sheared off flat rubber bearing

Flat shape laminated rubber isolators (S2=5) Figure 18 shows the time records of response of the mass as input 35 cm/s of JAM Kobe wave with the same order of 319.1 gal. The maximum response acceleration of the mass in Figure 4. The maximum acceleration of the shaking table was horizontal direction was 206.7 gal and the maximum total horizontal restoring force and horizontal displacement were 200kN and 0.147m respectively. Horizontal displacement of 0.147m was equivalent to 363% of the total rubber height of the laminated rubber isolator.

The sheared off isolators are shown in Figure 17, and the time records of the response of the mass of the input velocity of 45cm/s of JAM Kobe wave with the same order of Figure 4 are shown in Figure 19. In this case, at the horizontal displacement of 0.175m, all of the four isolators were sheared off simultaneously. After the isolators' shear-off, the mass landed on the restraints of the both side of the mass. So some shocks occurred in the mass as indicated in the time records of the accelerations in vertical and horizontal directions. From the observations, all of the shear-off phenomenon occurred in the rubber layer. Therefore the adhere force was enough to bear the breaking rubber shear strength. Figure 20 also shows the horizontal restoring force characteristics before the point of the breaking. In figure 21, the relation of the vertical stress and shear strain is shown.

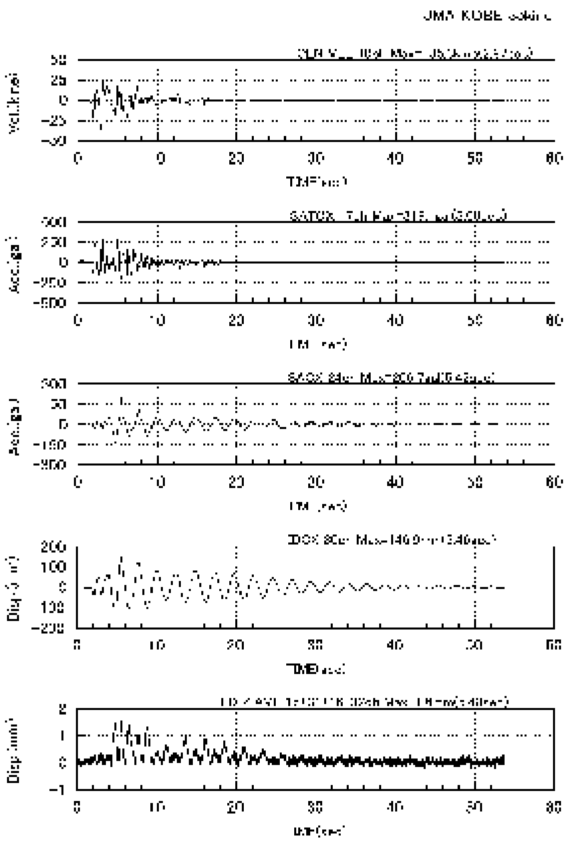


Figure 18 Time record of 35 cm/sec input

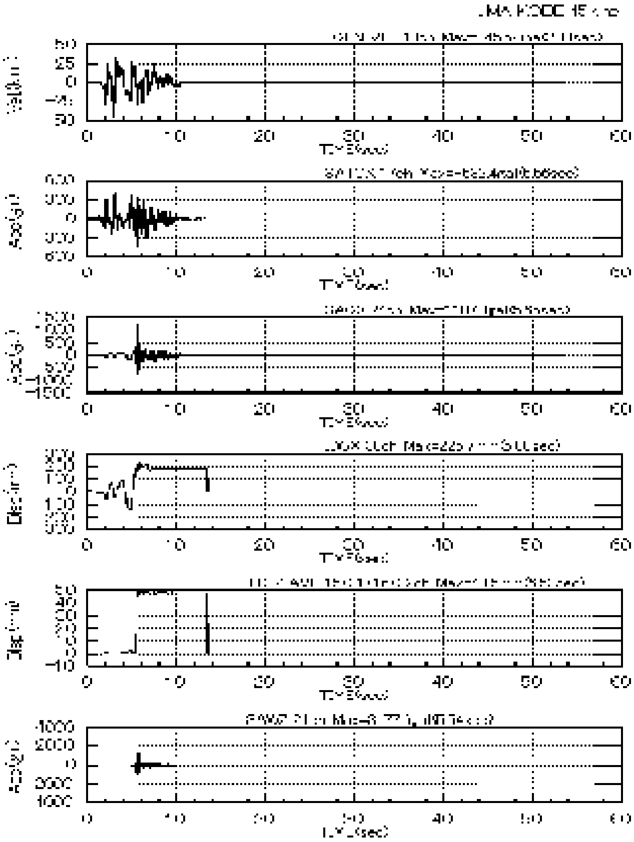


Figure 19 Time record of failure input 45cm/sec

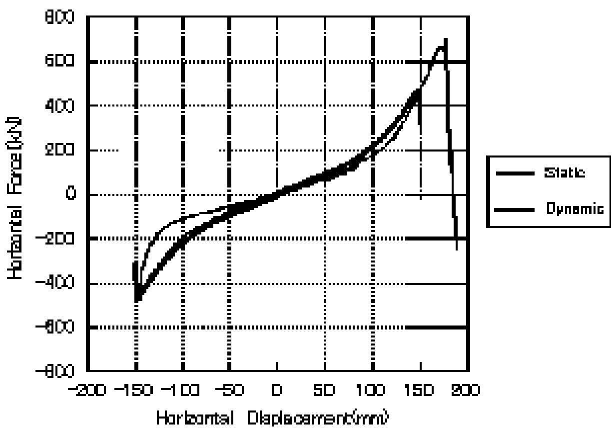


Figure 20 Restoring Force Characteristics

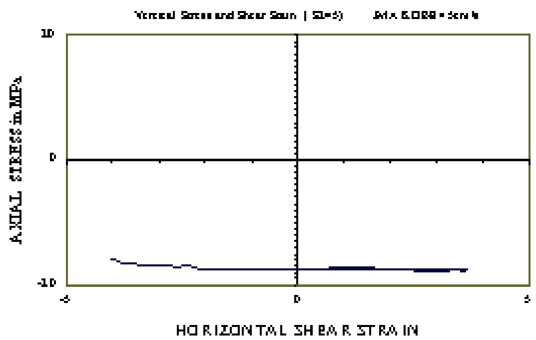


Figure 21 Vertical Stress and Horizontal Strain

STATIC FAILURE TEST RESULTS

Static failure tests were conducted by the bi-axial loading test machines. In this test, the isolator was loaded a vertical load of 500kN and sheared up the its breaking displacement with a constant shear velocity of 1cm/s. The ultimate strength of the S_2=5 sample was measured as shown in Figure 22.

The laminated rubber isolators of slender shape (S_2=2.76) were also performed by v static bi-axial loading tests. In this test, the isolator also was loaded with a vertical load of 500kN and sheared up its buckling displacement with a constant shear velocity of 1cm/s. The horizontal restoring force and vertical displacement characteristics were measured.

Figure 6 shows the statically measured restoring force in comparison with dynamically measured result. From Figure 6 it can be seen that the restoring forces of the isolator of slender shape which were obtained from the dynamic loading tests were slightly larger than that of static loading tests.

Figure 23 shows the vertical load that is measured in the static loading test of the slender shape isolator. It was confirmed from this figure that the vertical load acting on the laminated rubber isolator was reduced when the horizontal displacement was increased. Therefore the difference of restoring force characteristic may larger than that of Figure 6 because of the shortage of a vertical load acting on the laminated rubber isolator in the static test as shown in Figure 23.

Figure 22 Static test of flat shape rubber bearing

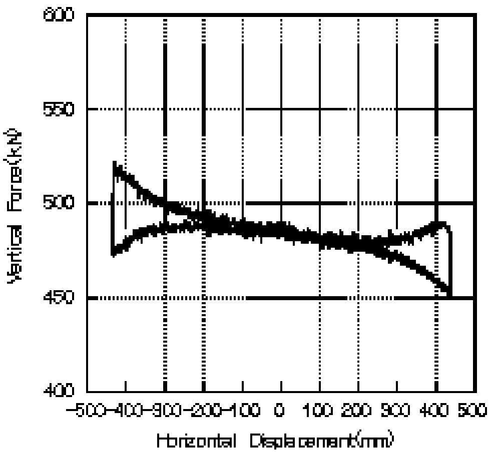


Figure 23 Vertical load measured in the static test

CONCLUSION

From the dynamic and static loading tests, we have following conclusions. (1)Horizontal restoring force could be estimated by measuring the acceleration of the mass. (2)In the case of the mass supported by the slender shape isolators, after the drop-down the mass was jumping up and was back to the original position without reduction of the restoring force and damage of the isolators. On the other hand, in the case of the mass supported by the flat shape isolators, after the shear-off the mass was continued to stay on the restraints because of no restoring force, and some shocks were occurred in the mass.

Some increments of the ultimate strength in dynamic loading tests were confirmed. This phenomenon probably was caused by the deformation speed dependency of the elastic modules of the rubber materials. When the laminated rubber isolators is deformed with the slow deformation speed, the contribution of bending deformation to the horizontal displacement becomes larger, and as a result, restoring force reduced. However the cause of this increment may be simply a dispersion of restoring force characteristic of laminating rubber isolators. Therefore we plan to measure the deformation speed dependency of the elastic modules of the rubber materials used for these isolators and the dispersion of the restoring force characteristic of laminating rubber isolators.

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