SHAKING TABLE TEST OF SIMPLE AND AFFORDABLE SEISMIC ISOLATION

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ABSTRACT :

Seismic isolation is one of very effective ways to mitigate damages to building/houses caused by earthquakes. However, the application is still limited to specific buildings and houses. The research and development project for disaster mitigation of developing countries started from 2006 by Building Research Institute Japan (BRI) in cooperation with the network of research institutes in earthquake prone area. The development of simple and affordable seismic isolation was selected as one of the study components in this project. For the purpose to evaluate possibility of simple and affordable isolation for developing countries, shaking table tests of two isolation systems were conducted in Building Research Institute. The Isolator systems were selected from viewpoint of feasibility for developing counties such as cost and simplicity, etc. One is sliding type base isolator made of stones. Several combinations of different stone types and surface finishing for upper and lower plates were tested. Another is laminated rubber bearing type device that was formed using layer of scrap tire pads (STP). Load-deformation curves of stone isolators and STP devices were obtained by the shaking table and cyclic loading tests. The performances of stone and STP devices were reasonable. Applicability of these devices on the seismic isolation system considering cost benefit was clarified.

KEYWORDS: Developing Countries, Performance, Seismic Isolation, Stones, Scrap Tires

1. INTRODUCTION

Seismic isolation is one of effective ways to mitigate earthquake damage of buildings/houses. Development of simple and affordable seismic isolation systems is needed for the purpose to mitigate damage of non-engineered buildings/houses in developing countries. Sliding base isolation is a very simple isolation system. Sliding type isolators using stones was proposed by Dr.Narafu of Building Research Institute[1]. Sliding base isolators using stones are tested and evaluated in this paper. Base isolation devices using scrap tire pad (STP), which has been proposed and studied by Dr.Turer[2], was also tested and evaluated in this paper. The possibility of using these devices for base isolation system is explored and discussed in this paper.

2. ISOLATORS

2.1. Sliding Type Isolators using Stones

Granite and Marble are selected for stones of sliding type isolators. Granite and Marble shown in photo 2.1.1 and photo 2.1.2 are commonly used for buildings in many countries. A pair of stones for upper stone pads and lower stone plates was prepared for the test. The upper stone pad is cylindrical in shape with 67mm in diameter and 25mm in thickness. The lower stone plate is cubic with 700x380x20mm dimensions. Surface of stones have mirror finishing (Mirror) and common finishing for back (Back). Surface roughness values (Rmax) of Granite were 0.02mm and 0.3mm in mirror side and back side, respectively. Surface roughness values of Marble were also 0.02mm and 0.05mm in mirror and back sides, respectively. Four pair's of Granite and Marble stones were prepared for the tests.

Photo 2.1.1 Pad of Granite

Photo 2.1.2 Pad of Marble

2.2. STP Devices

Scrap tire tread layers to construct STP device were collected in Japan and cut into pieces with dimensions of 180x150x11.5 mm. Laminated 10 layer STP device is shown in Photo 2.2.1. Different STP specimens were prepared using nails, glue and bolted rods for the purpose to increase their stability. A set of 10-layered STP devices was prepared by using 16 nails as illustrated in Figure 2.2.1. Additional 10-layered STP devices with commercially available glue placed between each pads were also prepared. 21-layered STP device was much taller to reduce the lateral stiffness and layers were bolted in the vertical direction by inserting two bolts (D=8mm) at two opposing corners as illustrated in Figure 2.2.2. The diameter of predrilled holes on STP pads was 16mm since 8mm bolts could not pass through smaller diameter holes due to existence of wire mesh inside the tread layers. Both ends of the bolts were connected to H shaped steel members of the upper and lower frames. Small sized STP layers were used for the washers of the bolts. These extra gaps provided for the bolt holes and STP washes did not increase the shear stiffness of the bolted STP units.

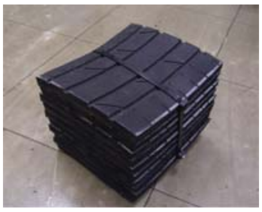

Photo 2.2.1 Laminated STP

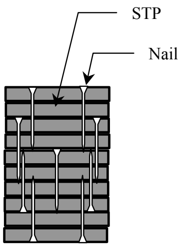

Figure 2.2.1 Nailed STP Device

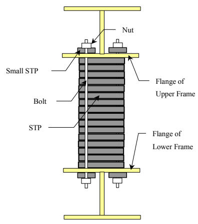

Figure 2.2.2 Bolted STP Device

3. TESTING METHOD

3.1. Shear Loading Test of Stone Isolators

For a preliminary test, shear loading test for sliding type isolators using stones is conducted. Loading method is illustrated in Figure 3.1.1. Load is applied for the supports holding the upper stones. Species of stones (Granite & Marble) and surface (Mirror & Back) is combined. Stainless Steel (SUS410) and Fluorine Regime are also used for the shear loading test for comparison. Shear load was applied by an actuator with 1 mm/s and 10 mm/s in velocity. Three tests were conducted for each combination of stones and surfaces. Pressure on the pads was 0.01MPa.

3.2. Shear Loading Test of STP Devices

Vertical and shear loading tests were conducted to make sure that basic performance of STP for vertical and shear directions are satisfactory. Figure 3.2.1 illustrates vertical and shear loading test of STPs. Two specimens of 10 layered and 21 layered STP were tested for vertical loading under 0.5, 1.25, 2.5, 4 MPa pressures, and shear loading under vertical 0.5, 1.25, 2.5, 4, 8 MPa pressures. Glued and nailed STPs were tested under 4 MPa pressure. Monotonic and cyclic shear loads were applied for long (180mm) and short (150mm) directions of STP. Cyclic shear strains of 10, 20, 30, 40, 50, 60% were applied.

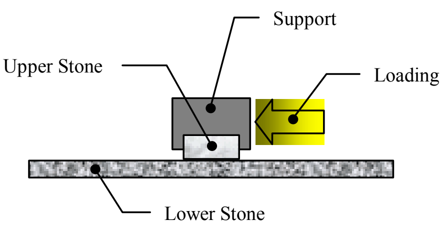

Figure 3.1.1 Shear Loading Test

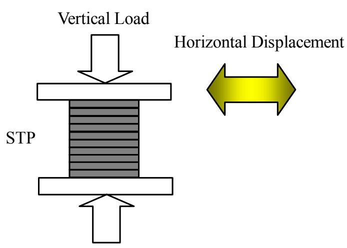

Figure 3.2.1 Vertical and Shear Loading Test

3.3. Shaking Table Test for Stone Isolators

Shaking table test of stone isolators is illustrated in Figure 3.3.1. A stone isolator consists of a pair of upper and lower stones. Four sets of stone isolators were installed at the corners between the upper and lower steel frames. The lower frame is fixed on shaking table. Vertical pressure on these pads was 0.55MPa. Input motion for the test was selected to be the NS component of the records observed at Japan Meteorological Agency Kobe during 1995 Hyogo-ken Nanbu Earthquake (Kobe NS). The maximum acceleration and velocity were 818gal and 90 cm/s. Scale of input amplitude for this test was 10, 25, 35, 50, 65,75% of the original motion.

3.4. Shaking Table Test for STP Devices

Shaking table test for STP devices is illustrated in Figure 3.4.1. The STP devices are installed at the four corners of shaking table between the upper and lower steel frames instead of the stone isolators. Stripe steel plates are used between STP devices and the frames preventing slip between them. Masses (weights) of steel blocks are used on the upper frame to change weight condition. Shaking direction is parallel to long (180mm) direction of STP devices. Input motions were pulse, random motion (Fourier amplitude constant in frequency 0.2-10Hz) and Kobe NS record.

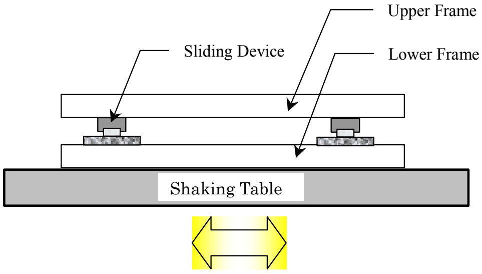

Figure 3.3.1 Shaking Table Test for Stone Isolators

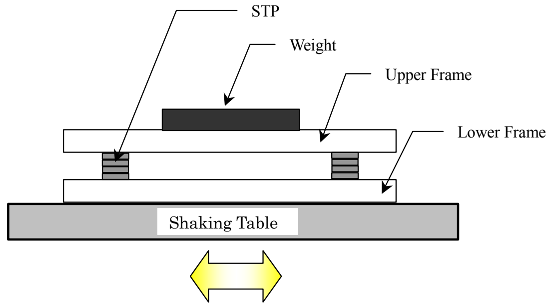

Figure 3.4.1 Shaking Table Test for STP Devices

4. RESULTS AND DISCUSSION

4.1. Friction Coefficient of Stone Isolators

Results from shear loading test of stone isolators are summarized in Table 4.1. The smallest friction coefficient using stone and stone was 0.19 of No.C using Granite(mirror) and Granite(back).

4.2. Response of Stone isolators in Shaking Table Test

In case of 75% of Kobe NS motion, results from shaking table test of stone isolators are summarized in Table 4.2. Specimen numbers in Table 4.2 are same as that in Table 4.1. Response acceleration – displacement curve of No.C is drawn in Figure 4.2.1. The maximum recorded response acceleration was 0.257g for No.J using Granite(mirror) and Marble(mirror). Response acceleration – displacement curve of No.J is shown in Figure 4.2.2. Vertical pressure on the pad was 50 times different between these two tests. Order of test numbers in Table 4.1 and Table 4.2 is different. It is considered that testing method for shear loading of these tests should be improved.

Table 4.1 Friction Coefficient Obtained from Shear Loading Test

	Specimens				Friction Coefficient		
	Lower Specimen		Upper Specimen				
No.	Material	Surface	Material	Surface	1mm/sec	10mm/sec	Ave
A	Granite	mirror	SUS410		0.14	0.17	0.16
B	Granite	mirror	Fluorine Resin		0.18	0.19	0.18
C	Granite	mirror	Granite	back	0.17	0.22	0.19
D	Marble	mirror	Marble	mirror	0.21	0.20	0.21
E	Marble	mirror	Granite	back	0.24	0.26	0.25
F	Granite	mirror	Granite	mirror	0.22	0.31	0.26
G	Marble	mirror	Marble	back	0.29	0.27	0.28
H	Marble	mirror	Granite	mirror	0.30	0.30	0.30
I	Granite	mirror	Marble	back	0.27	0.36	0.31
J	Granite	mirror	Marble	mirror	0.35	0.37	0.36

Table 4.2 Maximum Acc. in Shaking Table Test (Kobe NS 75%)

No.	Specimen				Maximum Acc.	Acc. Reduction
	Lower		Upper			
	Material	Surface	Material	Surface	G	Rate
J	Granite	Mirror	Marble	Mirror	0.257	0.53
B	Granite	Mirror	Fluorine. Resin		0.276	0.58
G	Marble	Mirror	Marble	Back	0.276	0.59
E	Marble	Mirror	Granite	Back	0.286	0.59
D	Marble	Mirror	Marble	Mirror	0.308	0.67
A	Granite	Mirror	SUS410		0.335	0.69
C	Granite	Mirror	Granite	Back	0.351	0.75
F	Granite	Mirror	Granite	Mirror	0.436	0.90

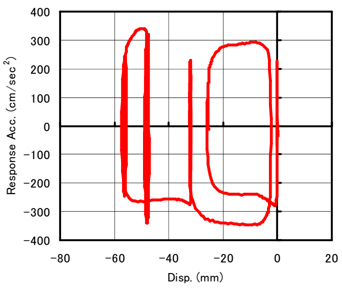

Figure 4.2.1 Acc.-displacement Curves of No.C Granite(Mirror)-Granite(Back) in 75% of Kobe NS

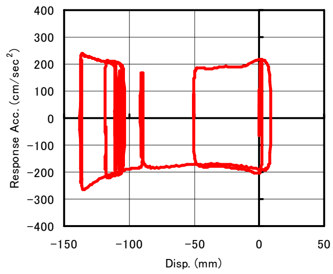

Figure 4.2.2 Acc.-displacement Curves of No.J Granite(Mirror)-Marble(Mirror) in 75% of Kobe NS

4.3. Load-displacement Curves of STP Devices in Vertical and Shear loading Test

Pressure – displacement curves obtained from monotonic vertical loading test of 10 and 21 layered STP devices are illustrated in Figure 4.3.1. The critical vertical pressures of 10 and 21-layered STP devices are suggested to be 20 and 10 MPa from Figure 4.3.1. Figure 4.3.2 illustrates pressure- displacement obtained from cyclic loading test of 10-layered STP devices under 0.5, 1.25, 2.5, 4 MPa with plus and minus 30% strain. Eqn. 4.1 indicates a definition of vertical temporary stiffness *Kv, w*here *Kv* is the vertical stiffness, σ is vertical stress, and δ is vertical displacement. Measured *Kv* values for the different vertical pressure levels of 0.5, 1.25, 2.5, 4 MPa are 0.176, 0.335, 0.785, 1.152 MPa/mm, respectively.

$$Kv = \frac{\sigma_1 - \sigma_2}{\delta_1 - \delta_2} \qquad (4.1)$$

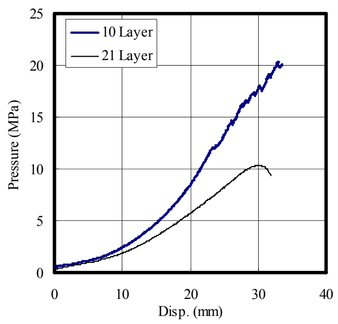

Figure 4.3.1 Vertical Pressure-Disp. of 10 & 21-Layer STP

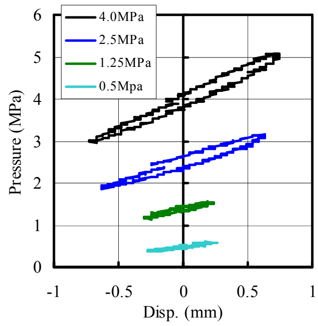

Figure 4.3.2 Cyclic Vertical Pressure-Disp of 10-Layer STP

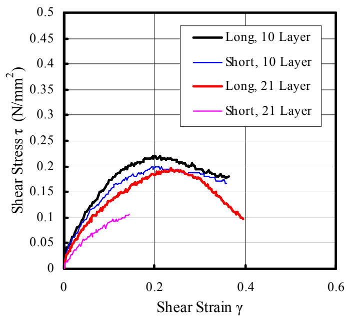

Figure 4.4.1 Shear Stress-Strain of 10 and 21- STP in 2.5MPa

4.4. Shear Performance of STP Devices obtained from shear loading test

Figure 4.4.1 illustrates shear stress (τ) - shear strain (γ) curves of 10 and 21-layered STP devices by monotonic shear loading for long (180mm) and short (150mm) directions under 2.5MPa vertical pressure. Relationships between shear modulus (G), shear stress (τ), shear strain (γ), horizontal load (P_H), horizontal cross-sectional area (A) of STP, horizontal displacement (δ_H) on top of STP devices and height *(H)* of STP devices are indicated in Eqn.4.2.

$$G = \frac{\tau}{\gamma} = \frac{P_H \cdot H}{A \cdot \delta_H} \qquad (4.2)$$

Shear stiffness (K_H) of STP devices is indicated in Eqn.4.3.

$$K_H = \frac{P_H}{\delta_H} = \frac{G \cdot A}{H} \qquad (4.3)$$

From Figure 4.4.1, the shear modulus G of 21-layered STP is found to be less than that of 10-layer, and shear modulus of STP for short directions is less than that of long direction. Figure 4.4.2 and Figure 4.4.3 show the horizontal load – displacement curves of 10-layered STP devices under 2.5MPa and 4MPa vertical pressures for the long direction, respectively. Amplitudes of shear strain are 10,20,30,40,50 and 60%. Bold line with square symbols indicates envelope curves connecting peak positions of each curve. Figure 4.4.4 indicates $\tau - \gamma$ curves of 10-layered STP devices for long direction under 0.5, 1.25, 2.5, 4 and 8MPa. Shear strains of Figure 4.4.4 indicate that the shear strains γ at peak positions on load-displacement curves of Figure 4.4.2 and Figure 4.4.3. The sudden changes of these curves in their maximum strain points indicate that unstable slips start to occur between each pad of STP devices. 4MPa of vertical pressures is suitable to constrain the unstable slip of 10-layerd STPs. Critical shear strains of 10-layered STP was around 40% under 2.5 or 4.0 MPa in vertical pressures.

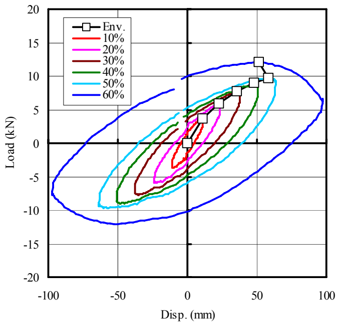

Figure 4.4.2 Horizontal Load-Disp. of 10-Layer STP in 2.5Mpa

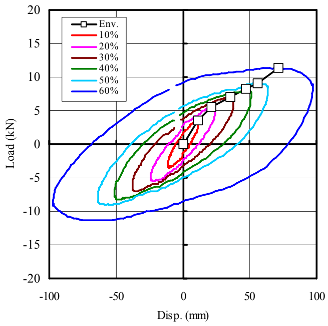

Figure 4.4.3 Horizontal Load-Disp of 10-Layer STP in 4Mpa

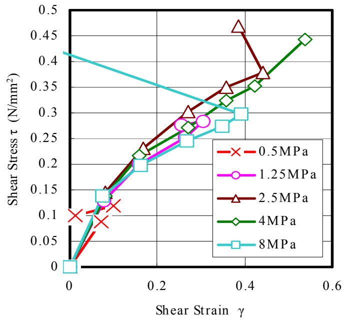

Figure 4.4.4 Horizontal Stress-Strain of 10-Layer STP, L-Direction

Figure 4.4.5 and Figure 4.4.6 illustrate horizontal load – displacement curves of 21-layered STP devices under 2.5MPa and 4MPa in vertical pressure for long direction. Amplitudes of horizontal displacement are 10,20 and 30% of *H*. Bold line with square symbol indicates envelope curves connecting peak positions of each load-displacement curves. Figure 4.4.7 indicates $\tau - \gamma$ curves of 21-layered STP devices under 0.5, 1.25, 2.5, 4, 8Mpa for long direction. Comparing Figure 4.4.4 and Figure 4.4.7, *G* of 10 and 21-layered STP is similar, but critical shear strain γ of 21-layered STP is almost half of 10-layered STP.

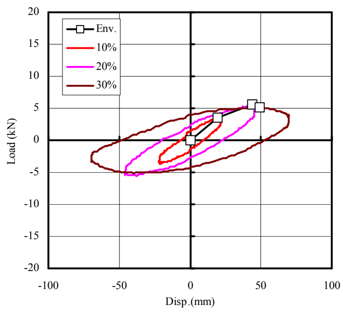

Figure 4.4.5 Horizontal Load-Disp. of 21-Layer STP in 2.5MPa

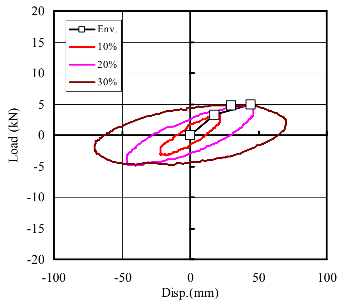

Figure 4.4.6 Horizontal Load-Disp. of 21-Layer STP in 4Mpa

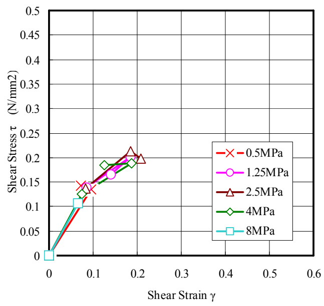

Figure 4.4.7 Horizontal Stress-Strain. of 21-Layer STP, L-Direction

4.5. Shear Performance of Improved STP Devices obtained from shear loading test

In order to increase the shear performance of STP devices, improved STP by glue, nail and bolt were tested in shear loading test. Figure 4.5.1 and Figure 4.5.2 illustrate horizontal load – displacement curves of 10-layered STP without and with glue under 4 MPa vertical pressure for long direction. Amplitudes of horizontal displacement are 10,20,30,40 and 50% of H. Bold lines with square symbol indicates envelope curves connecting peak positions of each load-displacement curves. Figure 4.5.3 indicates $G - \gamma$ and equivalent viscous damping factor *(heq)*-γ curves of 10-layered STP devices without and with glue under 4 MPa for long direction. These figures indicate glued STP has less *G* and *heq* than those of STP without gluing. Constant *heq* of glued STP indicates that glue of STP constrain the slip between each STP. It is observed that back sides of STP layers are shiny and slippery, which might be scraped off or roughened to improve the slippage strain and *G* of STP without and with glue. Figures 4.5.4 and 4.5.5 illustrate horizontal load – displacement curves of 10-layered STP without and with nails under 4 MPa vertical pressure for long direction. Amplitudes of horizontal displacement are 10,20,30,40 and 50% of *H* for the both figures. Additionally 60 and 70% of strain were added to the nailed STP tests. Figure 4.5.6 indicates *G*–γ and *heq*-γ curves of 10-layered STP devices without and with glue under 4 MPa of vertical compression for long direction. These figures indicate that nailed STP has almost same *G* and *heq* than those of STP without nailing. It is considered that nailing does not change *G* of STP. Although the nailing does not constrain the micro slipping between STP layers, but increases the shear deformability of STP devices.

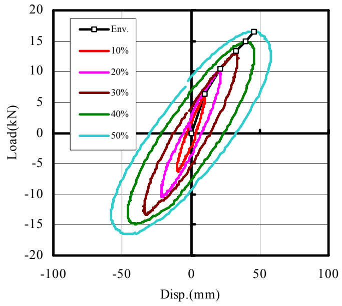

Figure 4.5.1 Horizontal Load-Disp. of 10-Layer STP in 4Mpa

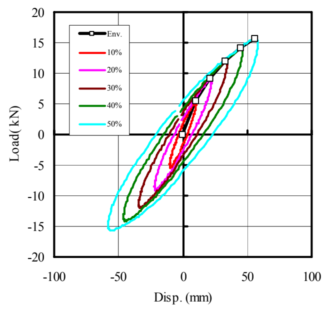

Figure 4.5.2 Horizontal Load-Disp. of Glued 10-Layer STP in 4Mpa

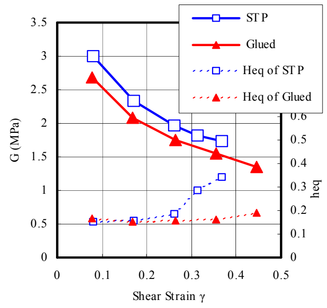

Figure 4.5.3 *G*-γ & heq-γ of 10-Layer (Glued) STP in 4MPa

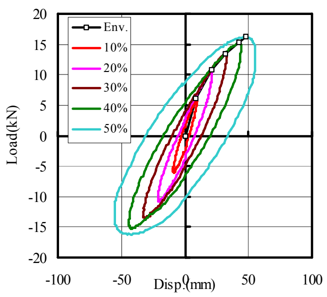

Figure 4.5.4 Horizontal Load-Disp. of 10-Layer STP in 4Mpa

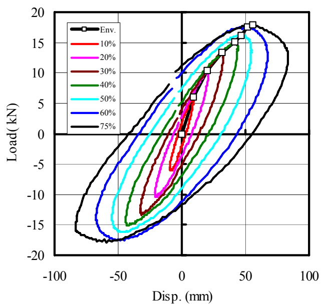

Figure 4.5.5 Horizontal Load-Disp. of Nailed 10-Layer STP in 4Mpa

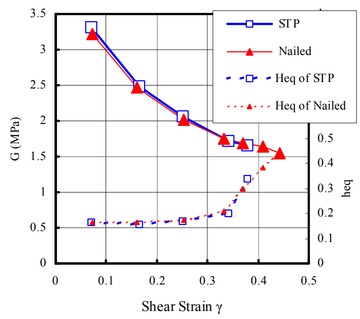

Figure 4.5.6 Shear Modulus & *heq* of 10-Layer (Nailed) STP in 4MPa

4.6. Shear Performance of Improved STP Devices obtained from Shaking Table Test

Nailed STP devices were subjected to shaking table test. Figure 4.6.1 and Figure 4.6.2 illustrate response acceleration and displacement of the upper frame on STP devices by Kobe NS 35% motion under 1.25 MPa of vertical pressure. Residual displacement of about 6mm is observed in Figure 4.6.2. Figure 4.6.3 illustrates load – displacement curves of 10-layered nailed STP by Kobe NS 35% motion. Bold line with cubic symbols in Figure 4.6.3 illustrates envelope curves obtained from shear loading test of 10-layered STP under 1.25MPa of vertical pressure in Figure 4.4.4. Figure 4.6.3 indicates the response of nailed STP by shaking table test follows the envelope curves that were generated by shear loading test.

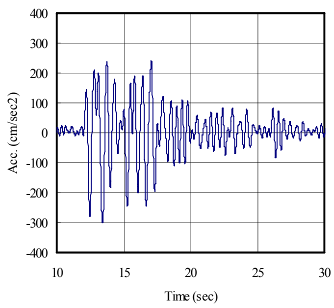

Figure 4.6.1 Acc.of 10-Layer Nailed STP by Kobe 35%

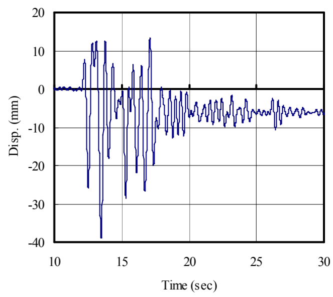

Figure 4.6.2 Disp. of 10-Layer Nailed STP by Kobe 35%

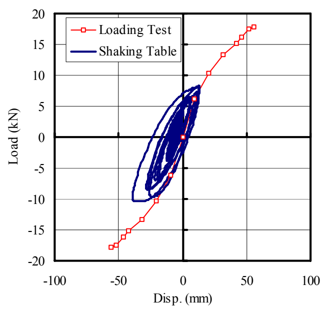

Figure 4.6.3 Load-Disp. of 10-Layer Nailed STP in 1.25Mpa

21-layered bolted STP was also applied by shaking table test. Figure 4.6.4 and Figure 4.6.5 illustrate response acceleration and displacement of the upper frame on STP devices by Kobe NS 35% motion under 1.25 MPa of vertical pressures. Residual displacement of about 7mm is observed in Figure 4.6.5. Figure 4.6.6 illustrates load – displacement curves of 21 layered nailed STP by Kobe NS 20% motion. Bold line with cubic symbols in Figure 4.6.6 illustrates the envelope curves obtained from shear loading test of 21-layered STP under 1.25 MPa in Figure 4.4.7. Figure 4.6.6 indicates the response of nailed STP by shaking table test follows the envelope curves by shear loading test.

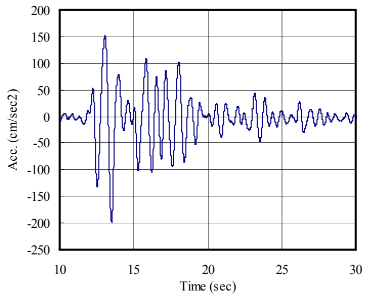

Figure 4.6.4 Acc. of Bolted 21-Layer Bolted STP by Kobe 20%

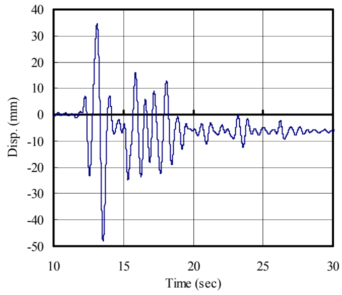

Figure 4.6.5 Disp. of 21-Layer Bolted STP by Kobe 20%

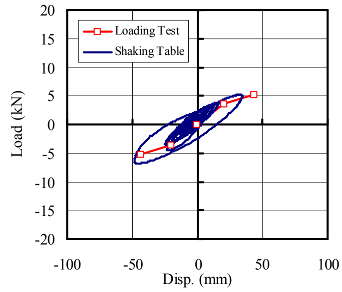

Figure 4.6.6 Load-Disp. of 21-Layer Bolted STP in 1.25MPa

Figure 4.6.7 and Figure 4.6.8 illustrate *G* - γ and heq-γ relationships of 10-layered nailed STP and 21-layered bolted STP by random motion and pulse motion. These *G* and *heq* are calculated from transfer function curves between upper frame and lower frame by random and pulse input. *G* decreases according to the increase of γ, but *heq* increase according to the increase of γ in Figure 4.6.7 and Figure 4.6.8.

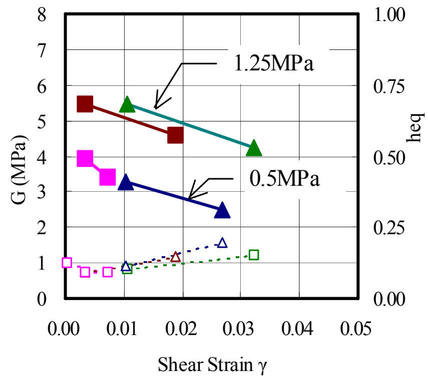

Figure 4.6.7 *G*(solid)- γ & *heq*(dot)- γ of 10-Layer Nailed STP in Random(■) & Pulse(▲) Test

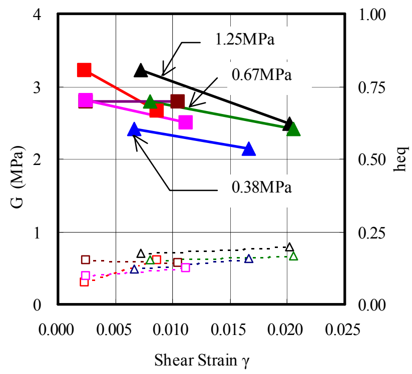

Figure 4.6.8 *G*(solid)- γ & *heq*(dot)- γ of 21-Layer Bolted STP in Random(■) & Pulse(▲) Test

4.7. Required and Expected Performance of STP for Isolation

Relationship between vertical pressure *(q)* on STP, shear modulus *(G)* of STP, pressured area *(A)* of STP, height *(H)* of STP and natural frequency *(T)* of seismic isolated structures is indicated in Eqn.4.4 for a single degree of freedom system. Figure 4.7.1 illustrates these relationships. In case of 10-layered STP; the natural period of the base isolation system is designed to be more than 2.5 sec, and vertical pressure (*q*) of STP must be less than 6 MPa, then shear modulus *(G)* of STP must be less than 0.5. But shear modulus *(G)* of 10-layed nailed observed in Figure 4.5.6 is more than 1.5. In order to realize base isolation system using STP, STP devices are required to have less shear modulus (*G*). Shear modulus *(G)* of rubbers for common laminated rubber bearings is around 0.3 MPa.. If we can improve STP to be more deformable, shear modulus *(G)* of STP will be reduced to 0.5. Elaborate glue of STP would be most possible way to realize excellent deformable STP. STP in Figure 4.5.1 to Figure 4.5.3 was glued by one of author. If skilled technician could glue STP, better performance of glued STP would be observed. As a matter of course, many ideas to improve STP should be tried.

$$q = \frac{mg}{A} = \frac{T^2 \cdot K_H \cdot g}{4\pi^2 \cdot A} = \frac{T^2 \cdot G \cdot g}{4\pi^2 \cdot H} \tag{4.4}$$

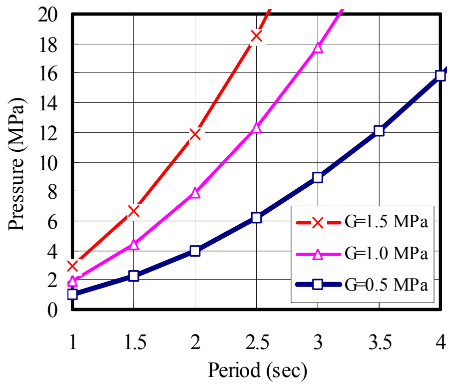

Figure 4.7.1 Required Shear Modulus (*G*) of 10-Layer STP for Target Period (*T*) under Vertical Pressure (*q*)

5. CONCLUSIONS

In order to develop simple and affordable seismic isolation system for developing courtiers, sliding type device using stones and rubber bearing type device using scrap tire pad were tested. From shear loading test and shaking table test of these devices, the following results were obtained.
From shaking table test of sliding isolators using stones, mirror finished Granite and Marble was found to be the most effective combination of stones for sliding type base isolation systems. Response accelerations of these isolators were constrained less than around 0.2G. This will be valuable finding for the development of simple and affordable seismic isolation.
Rubber bearing type devices using STP were tested in shear loading test and shaking table test. Basic performances of STP like as shear modulus *G*, vertical stiffness, critical vertical pressures and critical shear deformations were obtained from shear loading tests. Results of STP devices in the shaking table test clarified response of STP devices are in accordance with envelope curves obtained from shear loading test of STP devices. Finally, required and expected performance of STP devices for seismic base isolation system is summarized. Improvement of STP devices to increase shear deformability for base isolation system is expected.
The number of specimens used for these tests were limited. It should be considered the variation of each STP pad might be large, because STP pads are manufactured from scrap tires. Many scrap tires are come from many kinds and many brands of tires, and they have different residual thickness. Back coat of STP might be sensitive to the shear deformability of them. It would be important to select suitable scrap tires for STP devices from many scrap tires. Improve of STP devices should be continued to realize simple and affordable seismic isolation for the people in developing countries.

6. ACKNOWLEDGEMENT

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