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EARTHQUAKE ISOLATION SYSTEMS FOR BUILDINGS OF INDUSTRIAL FACILITIES USING VARIOUS TYPES OF DAMPER

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SUMMARY

For industrial facilities, earthquake isolation systems used for buildings should not only attenuate the seismic response of the buildings but also reduce the response of the internal equipment. Accordingly, dampers used for isolation systems should be evaluated mainly from this point of view. The performance of isolation systems using hysteretic dampers and viscous dampers respectively was examined by experimental tests and theoretical analyses. The results showed that the performance of isolation for the equipment depended on the damping characteristics, so that the choice of dampers should be done carefully.

INTRODUCTION

In Japan it is well recognized that energy absorption to limit the excessive deflexion of rubber bearings is an indispensable factor for base isolation systems for entire buildings. Energy absorbing devices are divided into two categories of hysteretic dampers (elasto-plastic dampers and friction dampers) and viscous dampers (oil dampers and viscous shear dampers). The performance of isolation for equipment in the buildings depends on damping characteristics of energy absorbing devices used for the isolation systems. Especially in the case of earthquake isolation of buildings of industrial facilities such as neuclear reactor power stations and semiconductor manufacturing factories which involve a lot of high sensitive equipment to vibrations, choice of dampers should be done very carefully because the performance of earthquake isolation for the internal equipment is a matter of great account in this case. From this point of view, earthquake isolation systems using hysteretic dampers and viscous dampers have been evaluated through both experimental tests of a 0.3 scale model of base-isolated building and the theoretical analyses, to find the most suitable systems for industrial facilities (Ref. 1,2,3).

TEST MODEL AND ENERGY ABSORBING DEVICES USED FOR TESTS

<u>0.3 Scale Model of Building</u> Photo 1 shows a 0.3 scale model of a supposed two-storey steel-frame building with a mass of 211,000 kg supported by four of the 490 kN rubber bearing (Ref. 4). The 5,700 kg superstructure in the scale model had natural frequencies of 13.3 Hz and 28.5 Hz when non-isolated, which corresponded to 4.0 Hz and 8.5 Hz respectively in the full scale building.

<u>Hysteretic Dampers</u> Figure 1 shows a friction damper. Installing under the superstructure, it produces the required friction force by pressing a friction pad

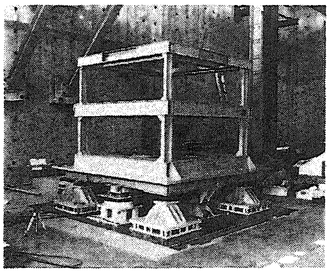

Photo 1 0.3 Scale Model of a Base-Isolated Building

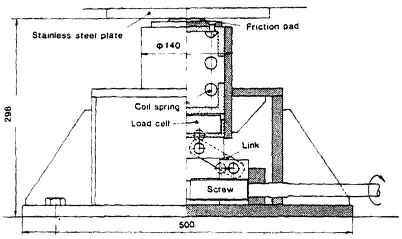

Fig. 1 Friction Damper

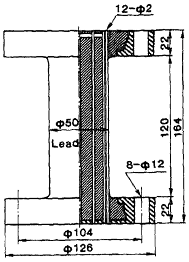

Fig. 2 Lead Shear Damper

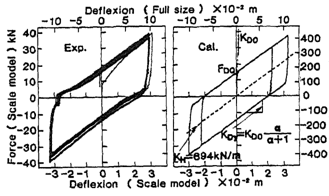

Fig. 3 Force-Deflexion Hysteresis Loop for the Lead Shear Damper

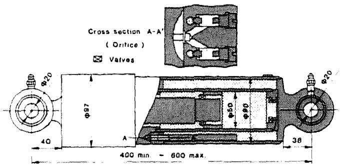

Fig. 4 Oil Damper

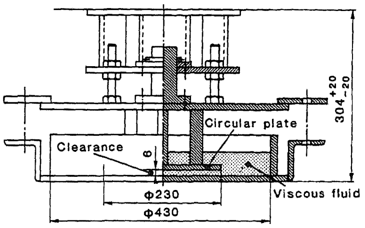

Fig. 5 Viscous Shear Damper

of special alloy through a coil spring against a stainless steel plate on the bottom of the superstructure. Figure 2 shows a lead shear damper. It contained 12 steel wires inside of the lead to make its deformation in pure shear and to absorb the energy effectively. The stiffness after yield could be neglected and, as shown in Fig. 3, the hysteresis loop was similar to that of a friction damper rather than that of normal elasto-plastic dampers of steel.

Viscous Dampers Figure 4 shows an oil damper which has been ordinally used for railway trucks and produces a damping force proportional to a relative velocity. Figure 5 shows a viscous shear damper, which produces a damping force proportional to the square root of a relative velocity by shearing a special viscous material (Ref. 5). In the case of using a material of high viscosity (a viscous material of 8.8 kN·s/m² at 25 °C was used for the tests), the damping force considerably depends on temperature.

EXPERIMENTAL AND ANALYTICAL PROGRAM

Two-dimensional, horizontal-vertical, seismic excitation tests were carried out. For all earthquake inputs used for the tests, times of the inputs were reduced by a factor of 0.3 and the maximum accelerations were increased by a factor of 3.33 (= 1/0.3) to 10 m/s² in horizontal direction and 5 m/s² in vertical direction. Both horizontal and vertical accelerations on each floor slab of the building and the shaking table and deflexion of rubber bearings were measured.

For the theoretical analyses, a four-degree-of-freedom model including the rocking motion was used. The energy absorbing devices were expressed as follows:

(1)Friction Damper: A Coulomb friction was assumed. In the tests, the friction force was set to be equivalent to the inertia force when the 5,700 kg mass of the building had an acceleration of 0.15 g which corresponded to 0.045 g in full size.

(2)Lead Shear Damper: The hysteretic behaviour of the lead shear damper can be expressed by the differential equation as follows (Ref. 6):

$$\dot{F}_D(t) = K_{D0}\cdot v\cdot\{1-\mathrm{sgn}(v)\cdot F_D(t)/F_{D0}\} \qquad (1)$$

where $F_D(t)$ is the restoring force, K_{Do} is the initial stiffness, F_{Do} is the yielding force and v is the relative velocity. The damper used for the tests had parameter values of K_{Do}=33.3 (MN/m) and F_{Do}=14.3 (kN), and regarding this hysteresis loop as that of a friction damper, the apparent coefficient of friction was equivalent to 0.26.

(3)Oil Damper: A linear damping force was assumed. Two oil dampers used gave the system a viscous damping of 22 % critical at 1st natural frequency for the sinusoidal excitation tests, but the damping ratio was reduced to 11.3 % for the seismic excitation tests which was shown by simulation.

(4)Viscous Shear Damper: The damping force produced by the dampers used can be written as follows:

$$F_D = 10.4 \cdot |v|^{0.5} \cdot \mathrm{sgn}(v) \quad (\mathrm{kN}) \qquad (2)$$

where v (m/s) is the relative velocity. The corresponding linear damping ratio was 16 % in the case of seismic excitation tests, and 20 % for the sinusoidal excitaion tests.

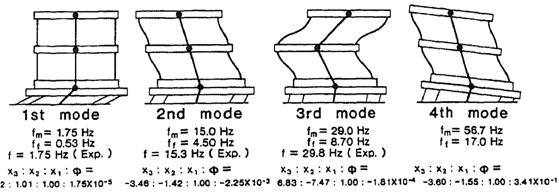

Fig. 6 Natural Frequencies and Mode Shapes of the Base-Isolated Building

Figure 6 shows the natural frequncies of the base-isolated building for both the scale model (f_m) and the full scale system (f_f), together with the mode shapes. The 1st mode (0.53 Hz) is a rigid body mode in which there is only deformation in the rubber bearings. The 2nd (4.50 Hz) and 3rd (8.70 Hz) modes have their natural frequencies in the range of dominant frequencies of earthquakes and the deflexions of rubber bearings are very small. Accordingly the dampers must respond to such small amplitude vibrations to reduce the responses of these modes which are important to the internal equipment. The 4th mode is the rocking mode which have the natural frequency higher than the dominant frequencies.

Performance of Earthquake Isolation for Building The seismic excitation tests produced the results shown in Fig. 7. For all types of damper for the El Centro input, the horizontal and vertical response accelerations of the superstructure when isolated and when non-isolated are compared. The response deflexions of the rubber bearings are also shown. The values in Fig. 7 can be scaled to full size by multiplying by 0.3 for acceleration and 3.33 (=1/0.3) for deflexion. It was shown that the hysteretic dampers effectively suppressed the deflexions of rubber bearings and the viscous shear dampers exceeded in reduction in acceleration, although it is difficult to compare the performance from the results directly because the damping forces produced by the dampers were not all the same. Even for the hysteretic dampers, however, the performance of isolation for the building is satisfactory.

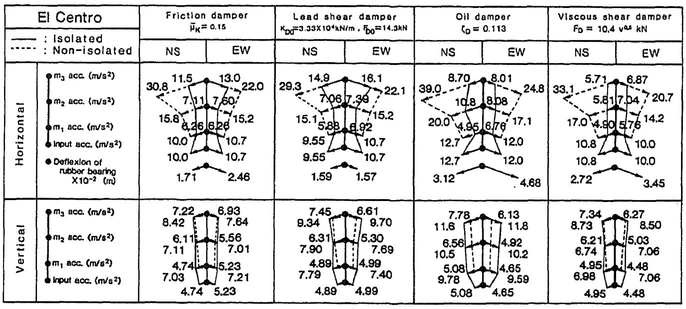

Fig. 7 Performance of Earthquake Isolation for the Building in the case of the El Centro Input

Performance of Earthquake Isolation for Internal Equipment Figure 8 shows the floor response spectra for four types of damper for the El Centro NS-UD input

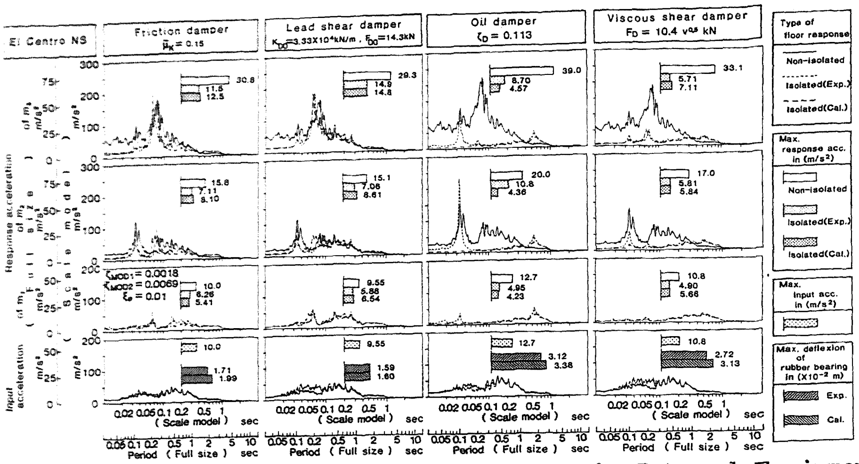

Fig. 8 Performance of Earthquake Isolation for the Internal Equipment in the case of the El Centro NS-UD Input

together with the spectra given by analyses where the damping ratio of equipment is 1 %. In the case of using the hysteretic dampers, the isolation effect in the range of frequencies higher than 5 Hz (0.2 s) in full size was satisfactory, but for the frequencies lower than 5 Hz, the isolation effect was unsatisfactory. In spite of the damping capacity of the lead shear dampers were larger than that of the friction dampers, the performance of isolation was about the same. If the capacity of enegy absorption were the same , the lead shear dampers would produce the better isolation effect than the friction dampers because of a roundish shape of their hysteresis loop. In the case of using viscous dampers, the oil dampers and the viscous shear dampers, both dampers achieved the better performance than the hysteretic dampers. But the oil dampers used did not work well for the 3rd mode vibration of the scale model with its 29.8 Hz frequency because the valves, installed in the cylinder in order to control oil-flows at the orifice in one direction, had no actions for the ripples of high frequencies. However, the viscous shear dampers were very effective for the range of such frequencies.

DEPENDENCES OF PERFORMANCE OF EARTHQUAKE ISOLATION ON ENERGY ABSORBING DEVICES

Since the damping forces produced by the four types of damper used for the tests were not equivalent to each other as mentioned before, further mathematical analyses were carried out to investigate the performance of isolation systems/dampers having an equivalent capacity.

Method of Investigation Three types of isolation systems using the lead shear dampers alone, the viscous shear dampers alone and a combination of both types of damper were examined. In this study, the dampers generating the same deflexion of rubber bearings to an earthquake input were regarded to have the equivalent capacity. Analyses were done for the full scale system using the four-degree-of-freedom model previously used for the scale model.

General Properties of Energy Absorbing Devices Figure 9 shows the floor response spectra for the Akita NS 0.25 m/s (1.67 m/s²) input (Nippon-Kai-Chubu Earthquake, 1983) in the case of using three types of damper having an equivalent capacity to generate the same deflexion of rubber bearings as that in a linear isolation system with 20 % of damping ratio, where the maximum response acceleration of each floor slab and the maximum deflexion of rubber bearings also are shown by the bar graphs for reference. Both the 1st and 2nd modal damping ratios of the superstructure were set to 2 % and 5 %. The 1st natural frequency of the base-isolated building was set to 0.5 Hz and the damping ratio of the internal

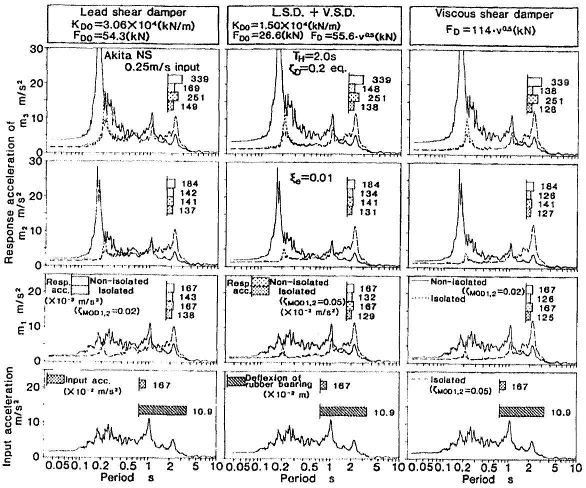

Fig. 9 Performance of Earthquake Isolation for the Internal Equipment (Akita NS 0.25 m/s input)

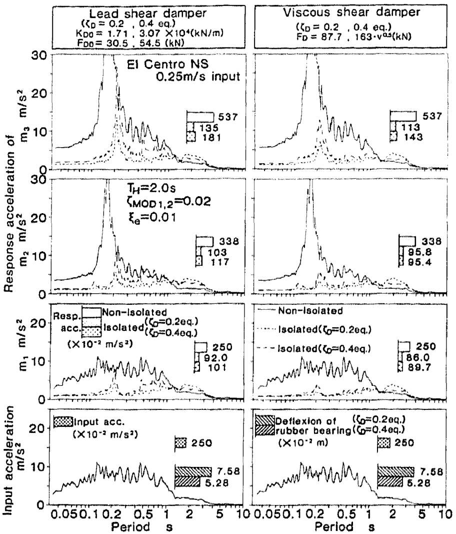

Fig. 11 Performance of Earthquake Isolation Affected by Increased Energy Absorbing Capacity of Dampers (El Centro NS 0.25 m/s Input)

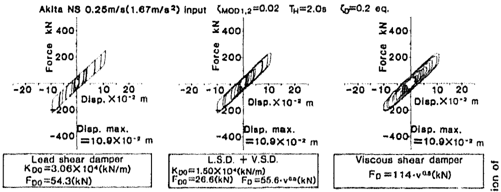

Fig. 10 Force-Deflexion Hysteresis Loops for Three Types of Damper (Akita NS 0.25 m/s Input)

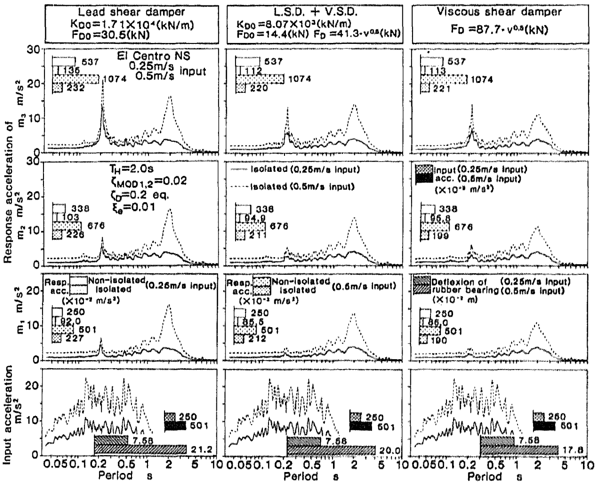

Fig. 12 Performance of Earthquake Isolation Affected by Increased Input Acceleration (El Centro NS 0.25 m/s Input)

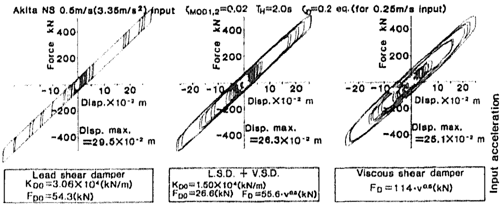

Fig. 13 Force-Deflexion Hysteresis Loops for Three Types of Damper (Akita NS 0.5 m/s Input)

equipment to 1 %. The performance of the earthquake isolation for the building itself was satisfactory in any type of damper, but for the internal equipment the lead shear damper was less effective in the range of frequencies between 1 Hz and 5 Hz compared with the viscous shear damper. Figure 10 shows the force-deflexion hysteresis loops for the dampers for the Akita NS 0.25 m/s input. The performance of earthquake isolation for the internal equipment is considered to be affected by the shapes of the hysteresis loops, therefore the viscous shear damper having the roundish hysteresis loop performed better than the lead shear damper especially in the range of higher frequencies.

Performance of Earthquake Isolation Affected by Increased Energy Absorbing Capacity of Damper Figure 11 shows the results for the dampers of increased capacity equivalent to the damping ratio of 40 % in the case of the El Centro NS 0.25 m/s (2.5 m/s^2) input. The accelerations in a frequency range around the 1st natural frequency of base-isolated building were reduced because the response deflexion of rubber bearings was suppressed to 5.28 cm compared with 7.58 cm in the case of 20 % damping ratio. At the same time, the performance in the range of higher frequencies became worse, especially for the lead shear damper.

Performance of Earthquake Isolation Affected by Input Conditions Figure 12 shows the results in the case when the El Centro NS 0.5 m/s (5.01 m/s^2) input was applied to the systems, which had been designed to have an equivalent capacity to 20 % of damping ratio for the El Centro NS 0.25 m/s input. The viscous shear damper could not only attenuate the response accelerations of the internal equipment in all ranges of frequency, but also suppress the excessive deflexion of rubber bearings more effectively than any other dampers. Figure 13 shows the force-deflexion hysteresis loops for the Akita NS 0.5 m/s (3.34 m/s^2) input. Comparing with Fig. 10, it is obvious that the viscous shear damper most effectively suppressed the deflexion of rubber bearings among three types of damper because the width of the hysteresis loop increased with the increased input. This means, even if the system suffers a large scale of earthquake never been supposed, the viscous shear damper always guarantee the performance of earthquake isolation and have the advantage of suppressing the excessive deflexion of rubber bearings.

CONCLUDING REMARKS

Judging from the performance of earthquake isolation only, the dampers having roundish shapes of hysteresis loops like the viscous shear damper are considered to have the most desirable properties for the earthquake isolation systems for buildings of industrial facilities. The lead shear dampers had the force-deflexion hysteresis loop similar to that of the friction damper, therefore the lead shear damper was not a representative of many kinds of elasto-plastic damper. In the case of normal elasto-plastic dampers using steel-bars, their hysteresis loops are more roundish, accordingly their performances in higher range of frequencies will be more satisfactory than that of the lead shear damper.

For semiconductor manufacturing factories which contain a lot of sensitive equipment, the viscous shear damper can be considered to be the most suitable type of damper. Moreover this damper is effective even for micro-vibrations with very small amplitudes of μm order, which is another advantage for this application. For nuclear power plants, however, the viscous shear damper is not suitable, because a very large capacity damper is difficult to make by this type and its damping force depends on air temperature. For the application, isolation systems using elasto-plastic steel dampers are possible as well as lead-rubber bearings and high damping rubber bearings.

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REFERENCES

1. Fujita, S., et al, Trans. of the Japan Soc. Mech. Eng., Vol. 53, No. 491, Ser.C, 1987 (in Japanese).
2. Fujita, S., et al, ibid.
3. Fujita, S., et al, Trans. of the Japan Soc. Mech. Eng., Vol. 53, No. 496, Ser.C, 1987 (in Japanese).
4. Fujita, T., et al, Trans. of the Japan Soc. Mech. Eng., Vol. 53, No. 485, Ser.C, 1987 (in Japanese).
5. Hayamizu, Y., et al, Prepr. of the Annual Convention of the Architectual Inst. of Japan, Oct. 1984 (in Japanese).
6. Bhatti, M.A. and Pister, K.A., Int. J. Earthqu. Engng. Struct. Dyn., Vol. 9, No. 6, (1981), 557.