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Structural control for seismic load using viscoelastic dampers

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ABSTRACT : In this paper, the vibration characteristics of a twin tower with two 24-story steel-framed buildings is discussed. Both buildings have nearly the same structure and the same dimensions. The viscoelastic dampers, using viscoelastic material called Bitumen Rubber Compound (BRC), is installed in one of the two buildings as a passive control system. In the process of developing the viscoelastic damper device, many kinds of tests, such as the following, were carried out: The material tests of BRC to obtain the dynamic properties. The shaking table test of the reduced steel frame model. And the dynamic loading test of the 1/2 scale model of the wall with a viscoelastic damper.

In order to compare the vibration characteristics and the earthquake response behavior of the two buildings, a forced vibration test, a measurement of the ambient vibration and an earthquake observation of the twin buildings were conducted.

1 INTRODUCTION

Structural control methods to reduce the response of structures such as high-rise buildings or other flexible structures against seismic or wind loads are being very actively investigated, and many kinds of vibration control systems are being proposed as passive or active systems.

Devices based on the plastic deformation of mild steel and lead(Skinner 1975), friction damper devices(Pall 1987) and viscoelastic dampers(Mahmoodi 1972, Fujita 1990) were proposed and investigated. Some kinds of these dampers have been in use for a long time as wind vibration absorbers and have more recently been incorporated in a number of other buildings. Recently in Japan, many kinds of passive energy absorbing devices have been proposed and developed.

Steel dampers and friction dampers are adopted as the energy absorbing devices for the vibration of structure due to strong earthquake motion. On the other hand, a viscoelastic damper has been adopted as a wind vibration absorber. All energy absorbing devices have advantages and disadvantages and the selection of a damper will depend on the structure, the seismic condition and the wind environment.

In this paper, a passive vibration control

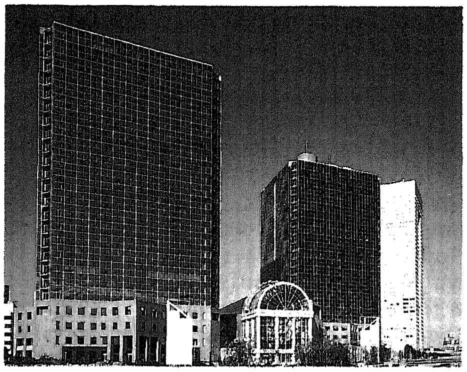


Photo 1 Exterior of SEAVANS (The South-Tower : Left)

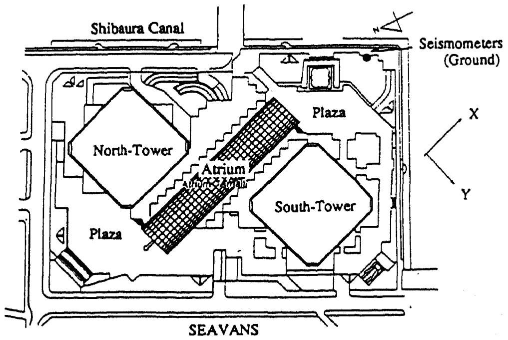


Fig.1 Buildings and Seismometers Arrangement

system of a high-rise building for earthquake induced vibrations and the vibration characteristics of a twin tower building called SEAVANS is described. Bitumen Rubber Compound (BRC) is used, as the viscoelastic material, in the energy absorbing device.

2 PROFILE OF THE BUILDINGS

SEAVANS is a twin tower 24-story steel-framed building. Both buildings, the North-Tower and the South-Tower, have nearly the same structure and same dimensions. The two buildings have a common reinforced concrete basement and a foundation directly supported by the underlying stiff gravel layer. An atrium building is located between the two towers. The maximum height of the twin towers is 98.8m and the typical floor area of each building is 2,730m^2 on each story. The South-Tower is the head office building of Shimizu Corporation. Photo 1 shows the exterior of SEAVANS. Fig.1 and Fig.2 show the arrangement and the section of the two towers. The seismometer arrangement is also shown in the two figures.

The viscoelastic damper system is installed in the X-direction of the South-Tower as a passive control system. It is adopted for both earthquake induced vibration and wind induced vibration of the building. Fig.3 shows a typical floor plan and the location of the partition wall in which the dampers are installed.

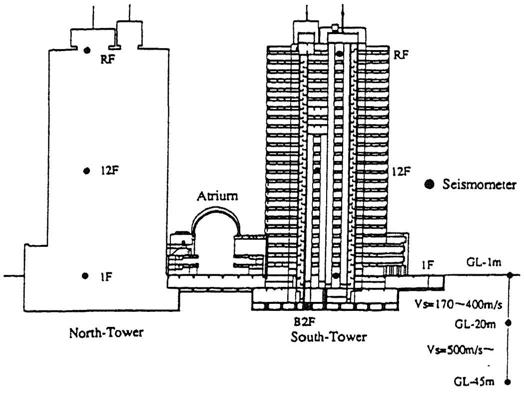


Fig.2 Elevation and Seismometers Location

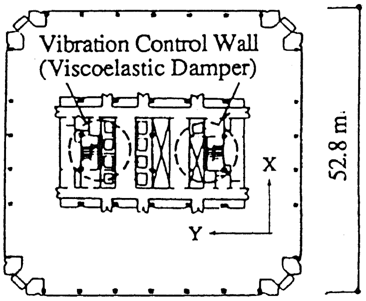


Fig.3 Layout of Vibration Control Walls

3 VISCOELASTIC DAMPER SYSTEM

3.1 *Viscoelastic Material*

The material (BRC) used in the damper is developed and manufactured by Showa Shell Sekiyu K.K. and Shimizu Corporation. BRC, made from thermoplastic rubber and bitumen, has the following features: (1) It can take the form of a sheet with any thickness. (2) The material itself has great adhesive strength and can adhere without any bonding agent. (3) It induced large damping force due to shear deformation. (4) It can sustain about 300% shear deformation to its thickness. (5) It is very stable with good aging properties, it is chemically inert and is resistant to environmental pollutants.

When used as the energy absorbing component in dampers, BRC is normally used in the form of shear layers and the exposed surface area is very small relative to the volume of material. Thus any chemical process that depends on diffusion, for example, moisture absorption or penetration, will be very slow.

The material properties are rather sensitive to temperature, frequency and strain. So, in the process of developing the viscoelastic damper system the following tests were carried out: The material tests of BRC under various conditions to obtain the dynamic properties. The shaking table test of a reduced steel frame model. And the dynamic loading test of two 1/2 scale models of the wall with a viscoelastic damper. From the results of these tests, the behavior characteristics of the material became predictable at a certain temperature, frequency and strain.

Viscous shear force (Q), equivalent viscous damping (C) and shear stiffness (K) against shear velocity of BRC (thickness d=0.5cm, shear area A=100cm^2, temperature t=19.5℃) are shown in Fig.4, Fig.5, Fig.6, respectively. Q, C and K depend on the temperature and the frequency of load. A 5℃ rise in temperature decreases both Q and C by about 13% each.

3.2 *Viscoelastic Damper*

The viscoelastic damper, as shown in Fig.7, has steel sheets and BRC sheets laminated alternately resulting in a multiple number of layers. In the case of SEAVANS, two vibration control walls with a viscoelastic damper are set as partition walls near the elevator core of each floor. The total area of the BRC sheet having a thickness of 0.5cm is 5.5m^2 on each

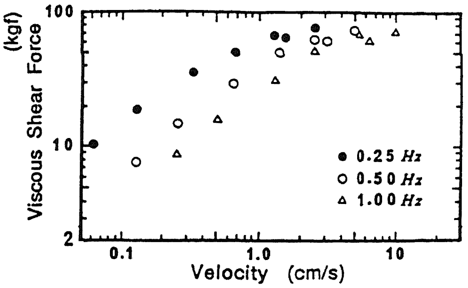


Fig.4 Viscous Shear Force-Velocity Relationship

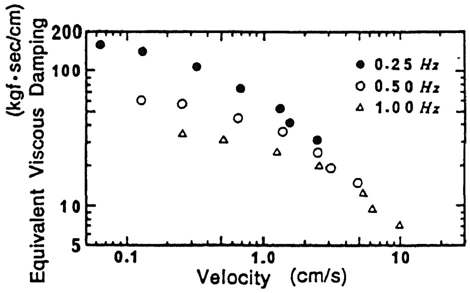


Fig.5 Equivalent Viscous Damping-Velocity Relationship

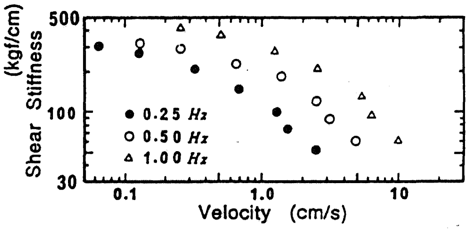


Fig.6 Shear Stiffness-Velocity Relationship

(Thickness d=0.5cm, Shear Area A=100cm², Temperature t=19.5℃)

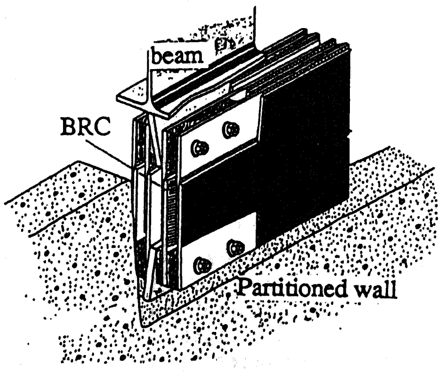


Fig.7 Viscoelastic Damper

floor. The viscoelastic damper system makes it possible to reduce the vibration of the building under an earthquake or strong wind.

4 RESULTS OF THE VIBRATION TEST

4.1 *Vibration Tests of Model Structures*

The model frame for the shaking table tests is shown in Fig.8. BRC was incorporated in the damping device which was attach to each story. In the experiments, the area of BRC in each device was varied. The fundamental natural frequency and the damping factor of the test frame under white noise excitation were in the range of 1.14Hz to 1.67Hz and 0.0016 to 0.15 of critical damping respectively. From the results of the shaking table test of the 6-story model frame, both the dynamic properties and the damping effectiveness of the BRC were confirmed(Shiba 1989, Fujita 1990). Fig.9 shows an example of the simulation analysis of the test frame of which an equivalent damping factor was 0.095. The coefficient of equivalent viscous damping and the shear stiffness of BRC were estimated by the regression analysis of the material test. In the analysis, the regression results were used and the non-linear effect of the BRC was taken into consideration. The simulation results agree well with the experimental results.

In order to investigate the damping effect and to obtain the dynamic load-displacement relationship of the wall model with viscoelastic damper, the dynamic loading test of the 1/2 scale model was conducted and an analytical model of the load-displacement relationship is obtained. Fig.10 shows the typical load-deformation relationships of a half scale vibration control wall model shown in Fig.11, and a stable damping characteristic can be seen.

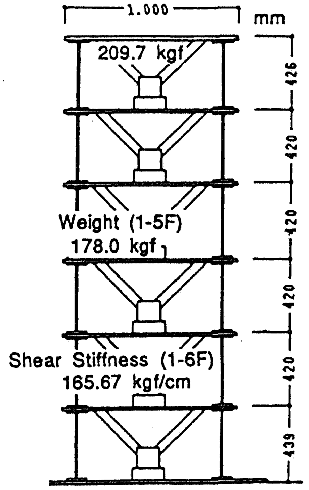
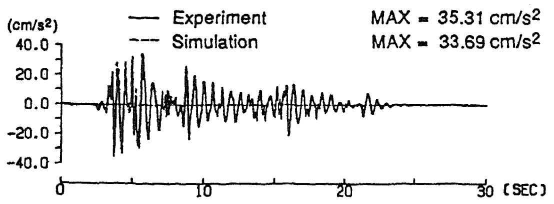
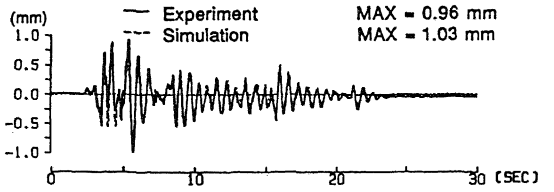


Fig.8 Model Frame



(a) Response Acceleration of the Top



(b) Response Displacement of the 1st story

Fig.9 Simulated Time Histories of Model Frame (Input Motion: El Centro 1940 NS, Max.Acc.: 50cm/s²)

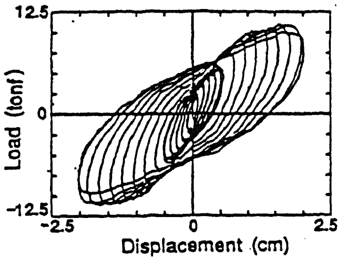


Fig.10 Load-Displacement Relationship of Vibration Control Wall (1/2 Scale Model)

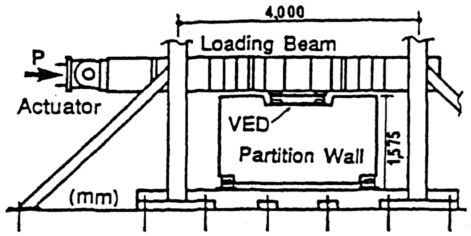


Fig.11 Loading Test System and 1/2 Scale Model

4.2 *Response analysis of the South-Tower*

On the basis of the results of the model tests and the material tests, the viscoelastic damper for the South-Tower of SEAVANS was designed and the earthquake response of the building was estimated. Fig.12 shows the maximum response of the South-Tower while being subjected to the input motion of El Centro 1940 NS. In this analysis, the maximum acceleration of input motion is reduced to 80cm/s², and the damping factor of the building without added damper is assumed to be 0.02 of critical damping. The fundamental period of the building analytically obtained is 3.04 sec. The earthquake responses of the structure with and without added viscoelastic dampers are compared. From the result of the response analysis, it is found that the response acceleration of the building with added dampers is about 30% smaller than that without dampers.

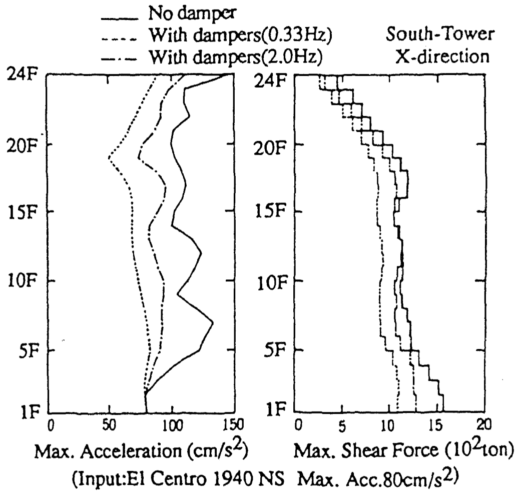


Fig.12 Response Analysis of the South-Tower

4.3 *Vibration Test of SEAVANS*

A forced vibration test for the South-Tower and a measurement of ambient vibration for both towers was conducted just before completion of construction.

Table 1 shows the result of the forced vibration test of the South-Tower. Four vibration modes were obtained in the X-direction and Y-direction respectively. Four torsional vibration modes were also obtained by the ambient vibration measurement. The natural periods of the building obtained from the vibration test are 27% shorter than those of the analytical model for the seismic design. The damping factors of each horizontal direction are in the range from 0.008 to 0.016 of critical damping. It is supposed that the reason for the difference of damping factors between two directions not being recognized is a very small vibration amplitude of the building. In other words, the shear deflection of the building caused by interstory drift did not transmitted enough to the dampers. Fig.13 shows the four natural mode shapes of the test results compared with those of the analytical results. Both mode shapes agree well with each other.

Table 1 Result of Forced Vibration Test of the South-Tower

MODE	X-DIRECTION		Y-DIRECTION	
	NATURAL FREQUENCY (Hz)	DAMPING FACTOR(%)	NATURAL FREQUENCY (Hz)	DAMPING FACTOR(%)
1	0.46	0.81	0.44	0.91
2	1.43	0.91	1.33	0.90
3	2.52	1.61	2.24	1.29
4	3.58	1.25	3.18	1.03

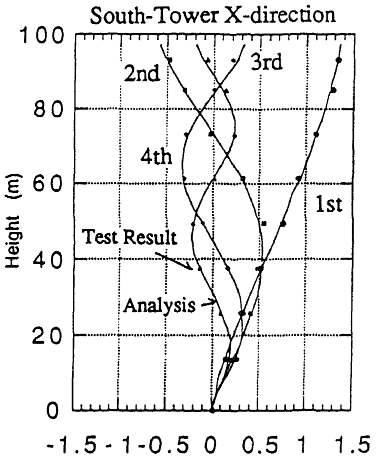


Fig.13 Vibration Modes of the South-Tower

5 EARTHQUAKE OBSERVATION

5.1 *Outline of Earthquake Observation*

In order to investigate and compare the vibration characteristics of the two buildings under a severe earthquake, an earthquake observation of the twin buildings was conducted. The three-component accelerometers were installed at seven measuring points in SEAVANS and at three measuring points in the ground, GL-1m, -20m and -45m. The seismometer arrangement is shown in Fig.1 and Fig.2. Totally, thirty components of accelerometers, three components of velocity seismometers at GL-45m, wind direction and wind velocity were measured and recorded with the earthquake observation system. The observation has continued since April, 1991. Twelve earthquakes were recorded during the past eight months. The maximum acceleration recorded at the top of the South-Tower was 32cm/s^2.

5.2 *Observation Results*

The vibration characteristics of the South-Tower during the earthquakes were studied. In order to identify the vibration characteristics of a structure during an earthquake, there are two typical methods. One is the frequency domain analysis by calculating the frequency response function with the FFT technique and the other is the time domain identification technique. It is supposed that the latter is more suitable to estimate damping characteristics of a light damping structure and non-linear structure. In this paper, natural periods and damping factors of the South-Tower were estimated by using the time domain identification technique. The estimation procedure is as follows: 1)Separation of each order of the natural vibration components of the recorded response time history by band-pass filtering. 2)Simulation analysis of one degree of freedom system with initial parameter value of natural period and damping factor, using acceleration wave form recorded on the first floor as the input motion. 3)Estimation of the difference between observed response wave form and analytical wave form. 4)Change of the value (natural period and damping factor) and iteration of simulation and error estimation. 5)Finally, obtaining the most suitable natural period and damping factor of each order vibration mode.

Fig.14 shows the earthquake response motions of the South-Tower recorded on November 19, 1991. The epicenter of this earthquake was Tokyo Bay and the magnitude was 4.9. Table 2 and Fig.15 shows the estimated natural periods and damping factors. It is recognized that the damping factors in the X-direction (added dampers direction) are larger than those of the Y-direction. The simulated responses of the 24th floor are compared with observed time histories with regard to each order of vibration mode. The result is shown in Fig.16.

The viscoelastic damper system is effective in reducing vibration of a high-rise building induced by earthquakes.

6 CONCLUSION

From the results of the vibration tests and the earthquake observations, it is recognized that the viscoelastic damper system is effective in reducing vibration of a high-rise building induced by earthquakes. The authors intend to continue the earthquake observation and verify the effectiveness of the viscoelastic damper system.

7 ACKNOWLEDGMENT

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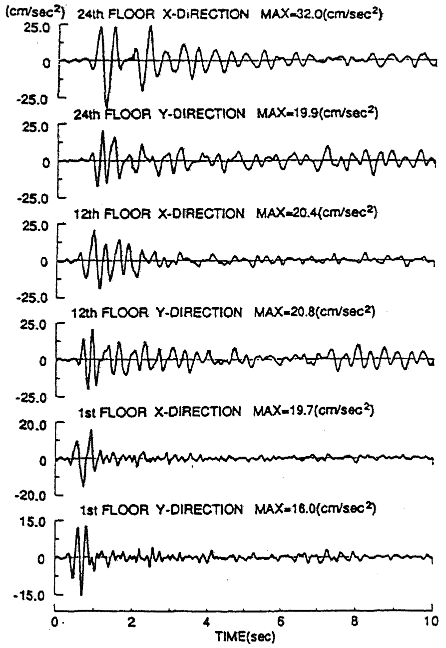


(The South-Tower : The Earthquake of Nov.19, 1991)

Fig.14 Observed Earthquake Motions

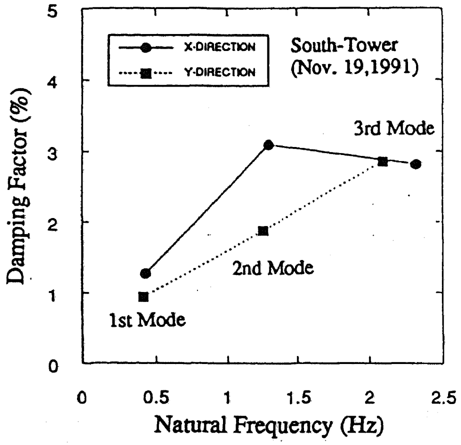
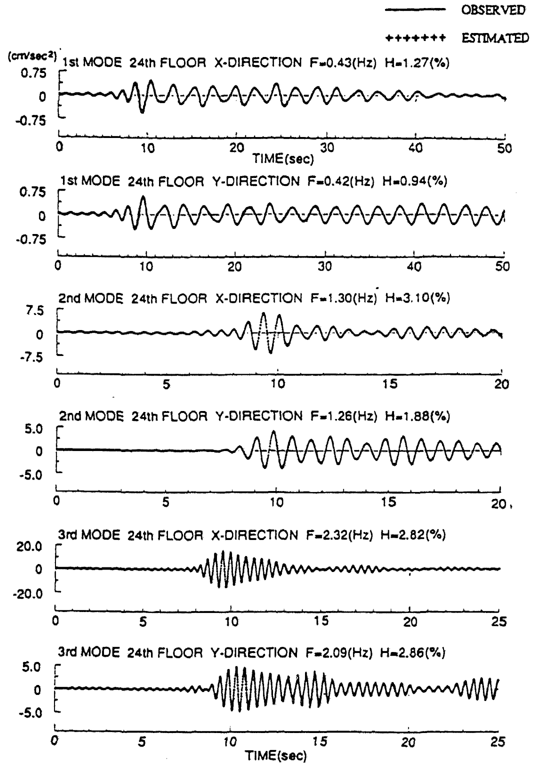


Fig. 15 Estimated Damping Factors

Table 2 Natural Frequencies and Damping Factors (The Earthquake of Nov.19, 1991)

MODE	X-DIRECTION		Y-DIRECTION	
	NATURAL FREQUENCY (Hz)	DAMPING FACTOR (%)	NATURAL FREQUENCY (Hz)	DAMPING FACTOR (%)
1	0.43	1.27	0.42	0.94
2	1.30	3.10	1.26	1.88
3	2.32	2.82	2.09	2.86



(The South-Tower : The Earthquake of Nov.19, 1991 Observed Wave Forms: Bandpass Filtered)

Fig.16 Simulated and Observed Time Histories

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