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AN ADVANCED BASE-ISOLATION SYSTEM FOR IRREGULAR BUILDING DESIGN

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SUMMARY

This paper introduces an example of the use of a semi-active base isolation system combining variable oil dampers with the conventional passive base isolation system. The system was developed to improve habitability by reducing acceleration during small and medium-level earthquakes. However, this is the first semi-active base isolation system in Japan to be certified as a highly reliable system that offers continued control even in the event of a major earthquake. The system is equipped with two types of oil dampers: passive dampers with a fixed damping coefficient and variable oil dampers that can be switched between two primary damping coefficients. In the event of an earthquake, the damping coefficient of the variable oil damper is changed as needed, based on an advanced control algorithm, to reduce the acceleration response of the building.

The building using this system is made up of a high-rise section and a low-rise section and an atrium that connects these two sections. The building is asymmetrical both horizontally and vertically. The use of a base isolation structure enabled the construction of a frame that was both streamlined and high in structural stability. In the following pages, an overview of the building design will be presented and the effect of using a base isolation structure on this building will be discussed. Subsequently, an overview of the semi-active variable damping system and the results of a time history response analysis in the event of a small or medium-sized earthquake will be presented, and the effectiveness of the system in reducing acceleration will be indicated.

INTRODUCTION

The construction of base-isolated structures in Japan began about 20 years ago, during the 1980s. Currently approximately 100 such structures are constructed in Japan each year, and the total number of base-isolated structures constructed in Japan exceeds one thousand. Initially in most cases this technology was used for structures with comparatively rigid structure, such as low- and medium-rise reinforced concrete buildings. The locations were limited to places with good ground conditions, so in most cases the base isolation story was placed at the foundation of the building. In recent years, however, the technology

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has also been used for high-rise buildings exceeding 100 meters in height, buildings of steel structure and others with a comparatively long period, and in an increasing number are intermediate story base-isolated structures in which the seismic isolation story is located at a level other than the building foundation. Moreover, the effectiveness of base-isolated structure has been confirmed for soft ground as well, and this technology has come to be used for a variety of building types.

The principal characteristic of base-isolated structures is that most of the energy applied to the building is absorbed by the seismic isolation story, reducing the load on the upper structure. In addition, this type of structure greatly increases the latitude of spatial composition for the upper structure. For example, even in cases with great eccentricity ratios that excite considerable torsional oscillation, making design difficult, the use of a base-isolated structure that combines the building center of gravity with the center of rigidity of the rubber bearings and damping elements enables the torsional oscillation of the building as a whole to be reduced. This paper will introduce a case study of the use of a base-isolated structure for a building made up of a high-rise section and a low-rise section, for which torsional oscillation could not be ignored. The use of a base-isolated structure in this case ensured high earthquake resisting performance and made streamlined design possible.

In general, seismic isolation systems are created by combining rubber bearings with oil dampers, steel dampers and other damping elements. The rubber bearing type also includes those in which the damping mechanism is added to the rubber bearing itself, as in the case of high damping rubber bearings and lead plug rubber bearings, as well as sliding bearings and other types that use friction resistance. In addition, oil dampers and steel dampers with various properties have also been developed, and the degree of latitude in design is increasing. Nevertheless, as all of these seismic isolation systems are passive in nature, the set damping properties are fixed, so the system is not capable of switching the damping properties to match the characteristics of the earthquake motion or the state of the building response.

In recent years, however, with the aim of reducing the sway of buildings to increase habitability, there is an extensive effort to develop active control systems that reduce sway by adding force in an appropriate manner based on the state of the building response [1], as well as semi-active base-isolation systems that switch the damping characteristics of dampers in an appropriate manner to match the state of the building response and are more effective than passive systems in reducing sway [2]. These systems are already being put to practical use [3]. Such control technologies have become possible due to recent advances in computers, sensors, actuators, variable oil dampers and so on, and further development is expected in the future. As seismic isolation technologies have matured to some degree, it is thought that applying these new control technologies in seismic isolation systems will enable the achievement of base-isolated buildings with even higher performance.

For example, in conventional seismic isolation systems that use passive oil dampers, setting a high damping coefficient for the dampers results in great transmission of energy to the upper structure, increasing the acceleration response of the building. Conversely, setting the damping coefficient to a value that is too low decreases the transmission of energy to the upper structure, but it also increases the relative deformation of the seismic isolation story. Thus, with such passive seismic isolation systems, there is a tradeoff between building acceleration and relative deformation of the seismic isolation story. In order to ensure that the deformation of the seismic isolation story is within the allowable value such as the clearance between the building and retaining walls in the event of a major earthquake, and to restrain the acceleration response in the event of a small or medium-sized earthquake, semi-active control that can switch the damping coefficient to match the state of the building response is effective. Accordingly, for this project it was decided to adopt a semi-active seismic isolation system in order to reduce the response acceleration in the event of primarily small to medium-sized earthquakes. This system is made up of two types of oil dampers, passive dampers and variable oil dampers, as well as sensors and a computer for control. In the event of an earthquake, the control computer calculates the ideal control signals, based on the information from the sensors that measure building response, and the variable oil damper switches the damping coefficient in an appropriate manner in accordance with these control signals. This paper will present the configuration of the semi-active seismic isolation system as well as the results of time history response analysis to show the effectiveness of the system in reducing the response.

STRUCTURAL DESIGN

Overview of building

The base-isolated building introduced in this paper is constructed in Tokyo. The building is made up of a high-rise section and a low-rise section connected by an atrium. Both frames are of rigid frame structure, with earthquake-resistant walls of reinforced concrete. Figure 1 shows a cross-sectional view. The high-rise section has three basement floors and 13 aboveground floors. The low-rise section has two basement floors and five aboveground floors; the first floor is the entrance on the low-rise section side. As there is a difference in elevation of approximately 10 meters at ground level on the site, the entrance on the high-rise section side is on the third floor.

The seismic isolation story is located between the second basement floor and the first basement floor. In order to provide seismic isolation for the entire building, the height of the retaining wall on the high-rise section side is approximately 25 meters due to the difference in elevation at ground level, and this is not desirable from the standpoints of safety and economy. Accordingly, for this project, intermediate story seismic isolation, in which the seismic isolation story is placed below the first basement floor (where it would have the least effect on building functions) was adopted. The high-rise section and low-rise section are structurally integrated by the first basement floor slab (the floor directly above the seismic isolation story), and a connecting passageway is provided on the fourth floor. The atrium, a space enclosed by glass, extends from the first basement floor to the fifth floor. Expansion joints are not used at the connections between the high-rise and low-rise sections.

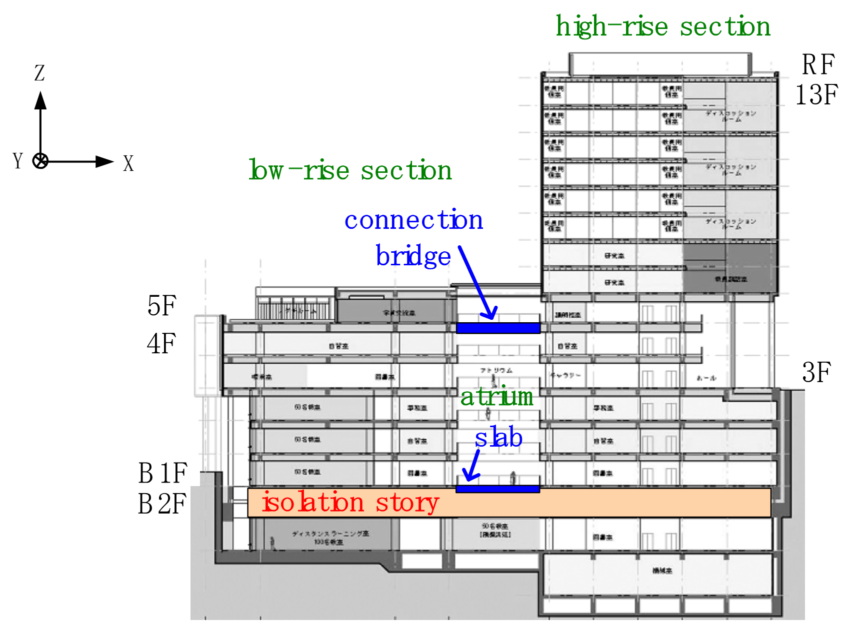


Figure1. Section View

Plan for seismic isolation story

The seismic isolation system for this building consists of rubber bearings and oil dampers. The rubber bearings are made of laminated natural rubber that possesses the linear restitution force properties and thin steel plates. All energy absorption on the seismic isolation story is accomplished by the oil dampers. Figure 2 shows the locations at which the rubber bearings and oil dampers are placed. The diameter of the rubber bearings is Φ700 mm -Φ1300 mm, and the secondary form factor S2 (an indicator of horizontal deformation properties) is 4.9 - 5.6. The shear strain at which the rubber exhibits stable restitution force properties is up to around 400%, while the horizontal displacement at that time is 560 mm for a bearing

diameter Φ700 (with a rubber height of 141 mm). The seismic isolation clearance between the building and retaining walls is 500 mm. Table 1 shows the eccentricity ratios for the seismic isolation story.
There are 10 oil dampers in both X and Y directions, making a total of 20. 10 of these are variable oil dampers and 10 are passive oil dampers. Table 2 shows specifications for oil dampers. The variable oil dampers are able to switch the damping coefficient between two stages. Both types of oil damper have bilinear damping force properties with respect to velocity. The primary damping coefficient is C_1 = 2.50 MN•s/m for the passive oil dampers and C_{1L} = 1.23 MN•s/m and C_{1H} = 3.68 MN•s/m for the variable oil dampers. The secondary damping coefficient is C_2 = 0.167 MN•s/m in both cases. In addition, the relief damping force for switching from the primary damping coefficient to the secondary damping coefficient is 785 kN in both cases; the velocity during relief operation differs depending on the primary damping coefficient. A detailed discussion of the variable oil damper and the semi-active variable damping system will be presented in the "SEMI-ACTIVE VARIABLE DAMPING SYSTEM" section later in this paper.

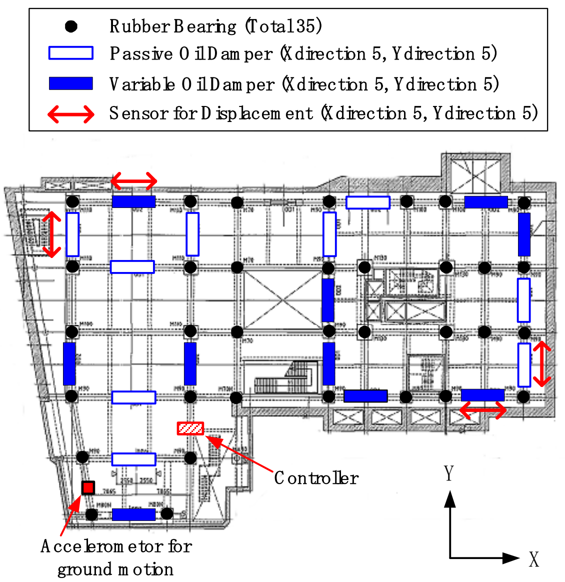


Figure2. Seismic Isolation Story Layout Plan

Table1. Seismic Isolation Story Eccentricity Ratios

	X direction	Y direction
Eccentricity Ratios	0.005	0.009

Table2. Specification for Oil Damper

	Primary Damping Coefficient (kN･s/cm)	Secondary Damping Coefficient (kN･s/cm)	Relief Damping Force (kN)	Relief Velocity (cm/s)	Maximum Damping Force (kN)
Passive Damper	C_1 = 25.0	C_2 = 1.70	800	32.0	1000
Variable Damper	C_{1H} = 36.8	C_2 = 1.67	785	21.3	
	C_{1L} = 12.3		785	63.8	

Analysis

Analysis model

The floors below the seismic isolation story are thought to behave together with the ground, so the range for modeling will be the seismic isolation story and above. As noted earlier, the upper structure is asymmetrical in both horizontal and vertical directions, and so the building response cannot be accurately evaluated with a simple parallel vibration model. For this reason, the low-rise section and high-rise section were modeled separately and connected by means of the connecting passageways on the floor just above the seismic isolation story and the fourth floor, in order to create a pseudo three-dimensional model that could appropriately evaluate parallel vibration and torsional oscillation. Figure 3 shows the analysis model. The mass points were derived by applying parallel vibration mass and rotational inertia at the centers of gravity on each floor in the high-rise section and low-rise section, and parallel vibration and direction of rotation were taken into consideration for the frame as well. The restitution force properties are linear up to the horizontal strength at the limited elastic region with respect to the load - deformation relationship (derived through static incremental analysis of the frame). The response was confirmed to be within the horizontal strength at the limited elastic region.
As the rubber bearings possess linear restitution force properties, modeling was done by consolidating the force at the centers of rigidity for both the high-rise section and the low-rise section and replacing the

parallel vibration spring in the X and Y directions with the rotational spring in the θz direction. The oil dampers were modeled at each installation location. The Maxwell model was used to enable the active properties of the oil dampers to be suitably evaluated.

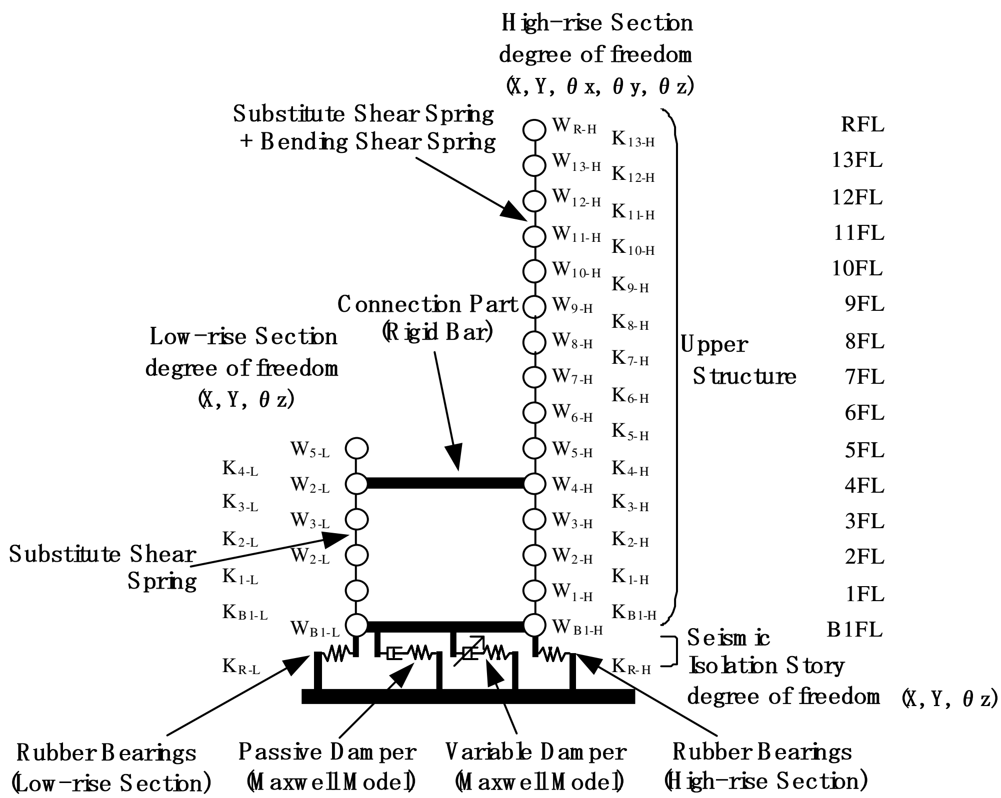


Figure3. Analysis Model

Eigen value

Table 3 shows the results of eigen value analysis using the model of the entire building including the seismic isolation story. This analysis does not take into account damping of oil dampers, internal viscous damping etc. The mode was one of great deformation on the seismic isolation story from primary through tertiary, with Y direction parallel vibration, X direction parallel vibration and θz direction in that order. The eccentricity ratio on the seismic isolation story was extremely low (1% or less), and for the parallel vibration mode the torsional elements were extremely small in both X and Y directions.

Table3. Results of Eigen Value Analysis

Mode	Natural Period (s)	Direction
1	4.26	Y
2	4.23	X
3	3.96	θz
4	0.87	Y
5	0.55	X
6	0.41	θz

Input earthquake ground motion

The building site was one with extremely solid ground conditions. The building foundation bed had an N value of approximately 100 or greater. For this reason, this building was planned with a spread foundation. The shear velocity, which indicates the likelihood of shear deformation in the event of an earthquake, was Vs = 490 - 550 cm/sec. For this project, three types of model earthquake ground motions were created as input earthquake ground motions. Of these three, two were chosen from the seismic environment at the project site; major earthquakes that had occurred in the past, the Ansei-Edo Earthquake of 1855 (M6.9) and the Great Kanto Earthquake of 1923 (M7.9), were used to envision and prepare models of the earthquake source faults, taking into account the propagation path to the site. Figure 4 shows the positional relationships for the site and each of the fault models. The other type of earthquake motion was made to fit the target spectrum at the building foundation level, in accordance with Japanese earthquake resistance standards. Figure 5 shows the pseudo velocity response spectrum. Table 4 shows a list of input earthquake ground motions. The standard observed waves (the 1940 EL CENTRO NS, 1952 TAFT EW, 1968HACHINOHE NS) are also used as a reference. The simulated earthquake motion was evaluated up to long period ranges of five seconds or more.

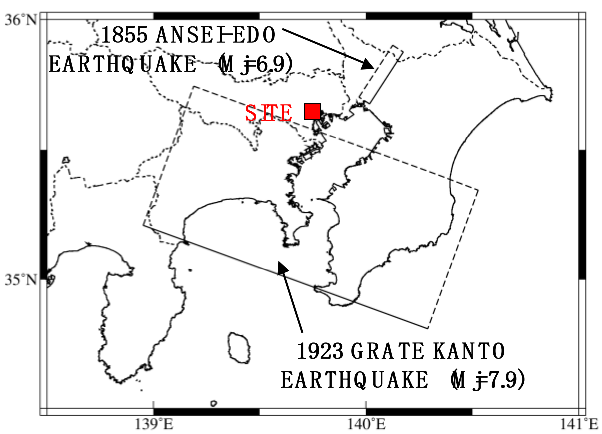


Figure4. Epicenter Positions

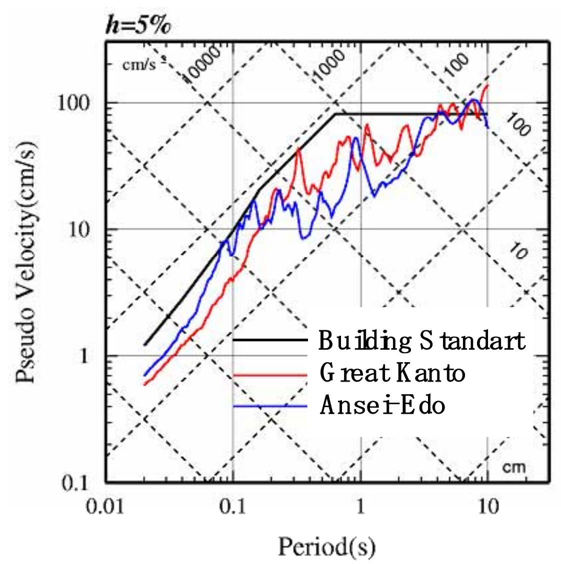


Figure5. Pseudo Velocity Response Spectrum

Table4. Input Earthquake Ground Motions

	Level2 Earthquake Motion		Level1 Earthquake Motion	
	PGA (cm/s^2)	PGV (cm/s)	PGA (cm/s^2)	PGV (cm/s)
Great Kanto Earthquake	160.9	43.6	-	-
Ansei-Edo Earthquake	251.0	37.2	-	-
Japanease Building Standart	401.9	56.2	-	-
1940 El-Centro NS	510.8	50.0	255.4	25.0
1952 Taft EW	496.6	50.0	248.3	25.0
1968 Hachinohe NS	330.1	50.0	165.1	25.0

Results of analysis

A maximum displacement in seismic isolation story is about 30cm for Japanese building standard input, and it is understood that a torsional deformation is not produced, since a difference of displacement between a high-rise section and a low-rise section is very a little. And maximum shear coefficients are less than elastic limits in all case.

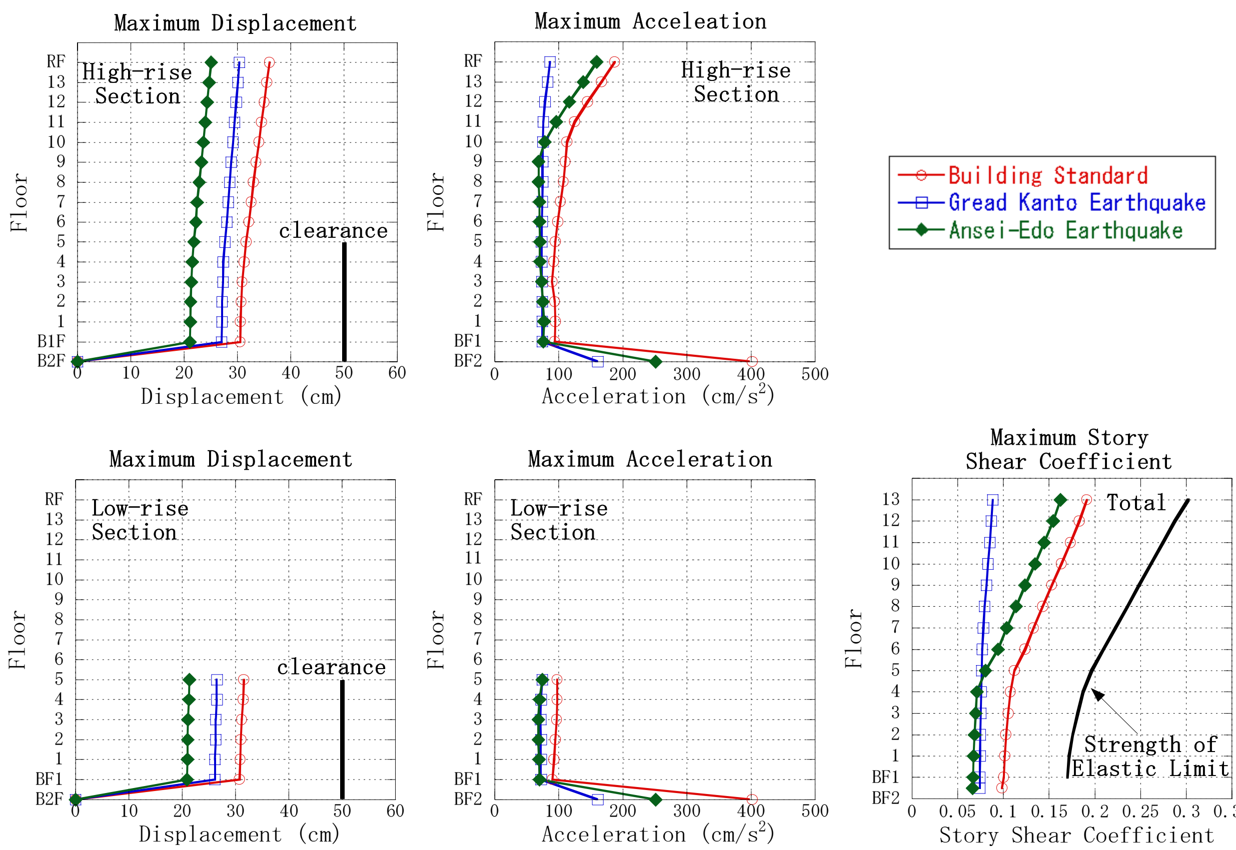
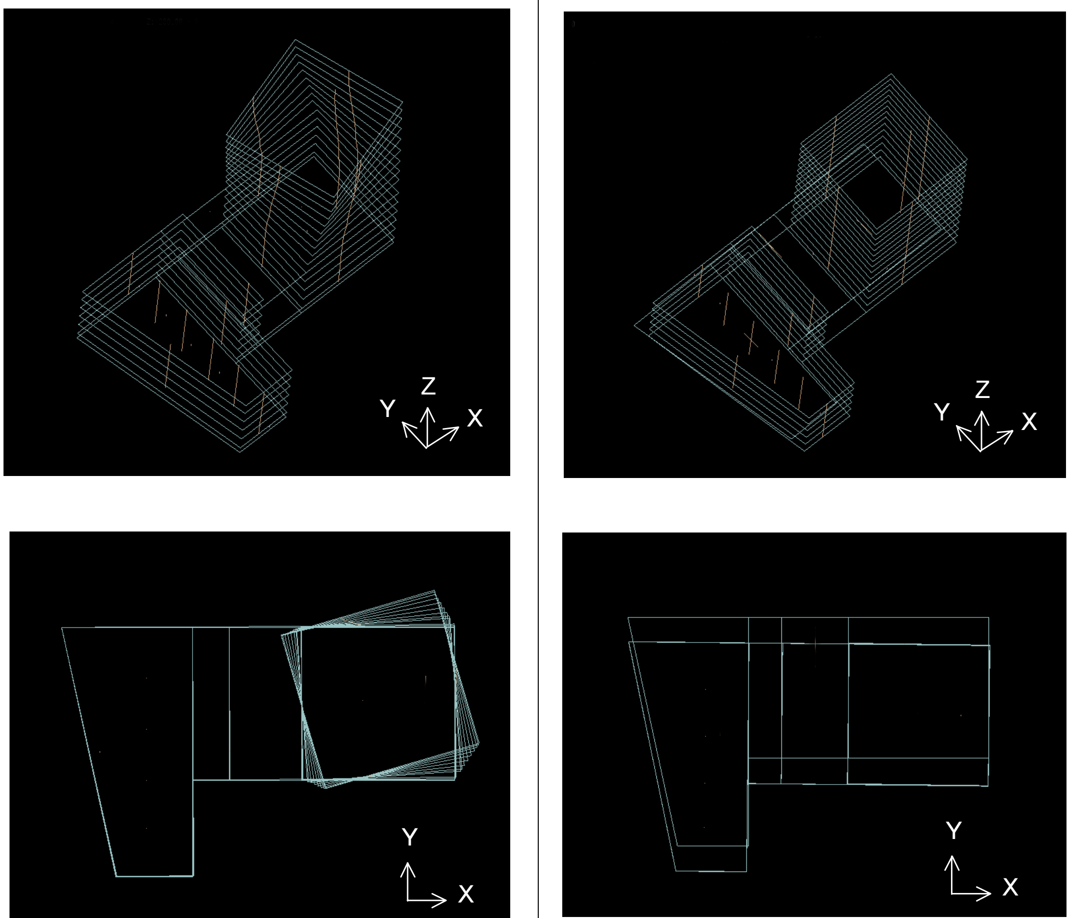


Figure6. Maximum Response in Y direction for Level2 Earthquake Motions

Comparison of non-seismic isolation and seismic isolation

The remainder of this section will present the effect of using a base-isolated structure for this project. Figure 7 shows the results of a time history response analysis for the non-base isolated model (fixed seismic isolation story) and the base-isolated model. The display magnification is five times the actual scale. The earthquake motion was input in the Y direction. In the non-base isolated model, torsion was excited throughout the entire building, and the torsional deformation was particularly noteworthy in the high-rise section. Conversely, in the base-isolated model, the seismic isolation story sustained considerable deformation, and no torsional deformation was produced in the upper structure. Even for frames like those in this building, in which the upper structure is asymmetrical and great torsional deformation tends to be produced in the upper structure alone, an appropriate seismic isolation system that combines the center of gravity with the center of rigidity on the seismic isolation story makes it possible to create a spatial structure that prevents torsional deformation and has extremely stable deformation properties.



Non-seismic isolation type	Seismic isolation type

Figure7. Comparison of Responses between Isolated Model and Non-isolated Model

SEMI-ACTIVE VARIABLE DAMPING SYSTEM

Overview of the system

Figure 8 shows the overall configuration of the semi-active variable damping system used for this base-isolation building with rubber bearings and oil dampers. Of the 20 oil dampers, 10 are variable oil dampers whose primary damping coefficient can be varied between two stages. The semi-active variable damping system is made up of these variable oil dampers and a controller (control computer) and various sensors such as displacement gauges and accelerometers. The sensors and variable oil dampers are connected by cables to the controller. Figure 9 shows the arrangement of sensors. The sensors constantly observe the upper structure sway, and the observed displacement of the seismic isolation story, the upper structure acceleration and the ground acceleration are transmitted instantly along the connecting cables to the controller. In the event of an earthquake, the controller puts the ideal control signals, in accordance with preprogrammed control laws, to switch the damping coefficient of the variable oil dampers. Control is conducted regardless of the scale of the earthquake (small/medium or large) to reduce the acceleration of the upper structure. Normally the damping coefficient for the variable oil dampers is set to the maximum value in order to suppress the structure sway caused by wind loads. In the event of sensor failure or power outage or other abnormality as well, the damping coefficient is automatically fixed at the maximum value. Even in the event that a major earthquake should occur in this situation, the system has been designed to ensure that deformation of the seismic isolation story will not exceed the clearance between the building and retaining walls.

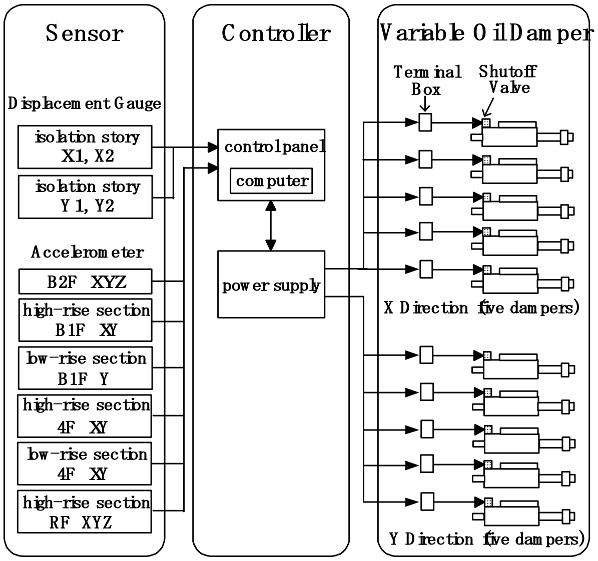


Figure8. Conceptual Diagram of System

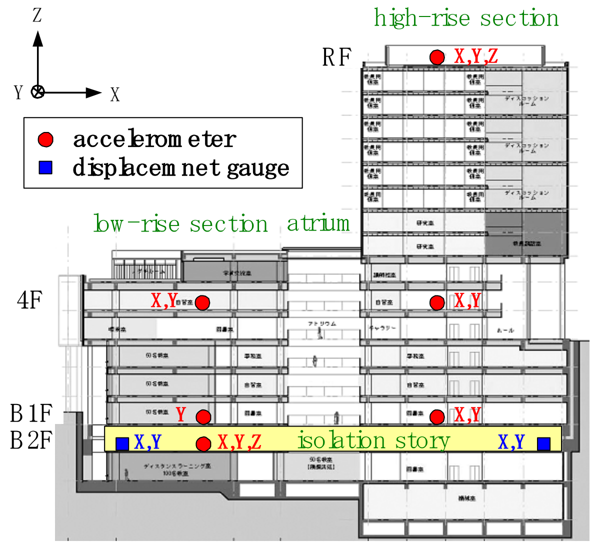


Figure9. Sensor Arrangement

Control law

A disturbance-accommodating sliding mode control law has been used as a control law [4,5]. This control law has been used because (a) sliding mode control, which is based on the nonlinear relay control, is suitable as the control law for semi-active control that switches the damping coefficient between two stages, and (b) this control law enables the control design for systems taking into account the disturbance dynamics, making it easy to put the primary focus of design on controlling absolute acceleration. There are four target modes for control: primary and secondary modes in the X direction and primary and secondary modes in the Y direction. Eight elements are observed for control: acceleration in X and Y direction at the top of the high-rise section, acceleration in the X and Y direction at the fourth floor of the low-rise section, acceleration in the X and Y directions at the second basement floor of the building and relative displacement on the seismic isolation story. The Kalman filter is used as the observer.

Variable oil dampers

The variable oil dampers have damping force characteristics that are bilinear with respect to velocity, with a primary damping coefficient and a secondary damping coefficient. Figure 10 shows the damping force characteristics. The primary damping coefficient consists of two values, C_{1L} = 1.23 MN•s/m and C_{1H} = 3.68 MN•s/m. The secondary damping coefficient for relief damping force or later is constant at C_2 = 0.167 MN•s/m. As in the case of passive dampers, the damping mechanism in the oil dampers consists of a main valve (regulating valve) and a relief valve, and the damping force is determined by the viscous resistance of the oil produced when it passes through the valve in accordance with the movement of the piston rod. The damper is switched from the primary damping coefficient to the secondary damping coefficient when the damping force reaches the relief damping force; at this point, the relief valve opens and the flow rate of the oil is controlled to switch the damping coefficient. This is the so-called "passive" mechanism. In a passive oil damper, the primary damping coefficient, secondary damping coefficient and relief damping force are set to predetermined values. In a variable oil damper, a main valve with a shut off valve (solenoid valve) is provided in addition to those noted above, and the shut off valve is opened and closed by means of electrical signals to switch the primary damping coefficient. The primary damping

coefficient is switched to C_{1L} when the shut off valve is open and C_{1H} when the shut off valve is closed. Figure 11 shows a mechanism of the variable oil damper. In addition, the shut off valve is open and closed in accordance with the supply of power (ON - OFF). On this system, power is normally not supplied (OFF) and the coefficient is set to C_{1H}; when power is supplied (ON), the valve opens and the coefficient switches to C_{1L}.
The dynamic loading tests were carried out to confirm the dynamic characteristics of the damper. The shaking was triangular wave oscillation by means of displacement control of hydraulic actuator (constant velocity oscillation), and the solenoid valve was opened and closed for both the expansion and contraction side of the damper. The time lag between the time at which the damping coefficient was switched and the time that the damping force reached the prescribed value (70% of target value) was extremely small (approximately 0.05 second).

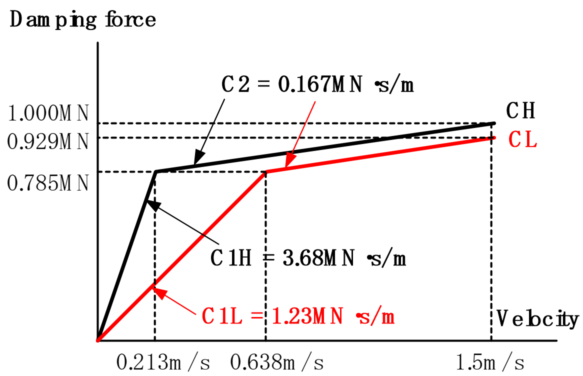


Figure10. Damping Force Characteristics

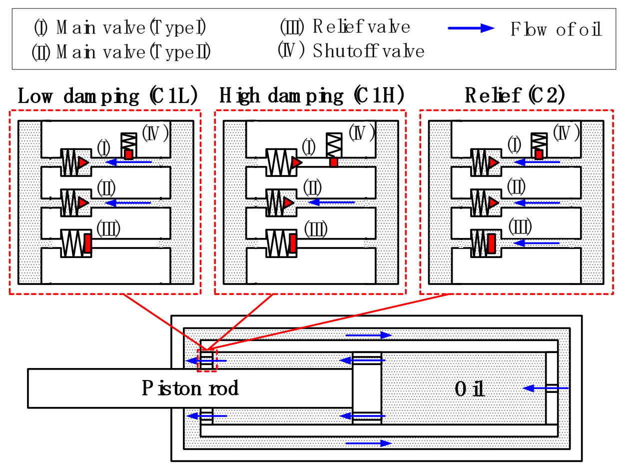


Figure11. Mechanism of Variable Oil Damper

Effect of semi-active base-isolation

To verify the effects of the semi-active variable damping system, we carried out time history response analyses of the semi-active and passive base-isolation systems and compared the vibration transmissibility and time history waveforms of the two base-isolation systems. In the analyses, the damping coefficients of the ten oil dampers in each direction of X and Y were set to $C_1 = 2.5$ MN•s/m for the passive base-isolation system, while five of the ten oil dampers were variable oil dampers and their damping coefficients were made switchable between $C_{1L} = 1.23$ MN•s/m and $C_{1H} = 3.68$ MN•s/m for the semi-active base-isolation system. Figure 12 shows the vibration transmissibility (the ratio of displacement of an isolation story to the input acceleration and the ratio of acceleration of top of the high-rise building to the input acceleration) comparatively for the two base-isolation systems. In the figure, the vibration transmissibility in the case where the damping coefficients of five variable oil dampers in each direction were all set to $C_{1L} = 1.23$ MN•s/m or $C_{1H} = 3.68$ MN•s/m are also shown. Incidentally, the vibration transmissibility were calculated from carrying out time history response analyses at the white noise input (at 0.05 Hz to 15 Hz) and determining transfer functions. The results of the analyses indicate that the two base-isolation systems have nearly comparable effects on the displacements of the base-isolation story, but the semi-active base-isolation system is more effective in the control of accelerations at the top of the high-rise section (particularly the secondary mode vibrations in the Y direction) than the passive base-isolation system.
Figure 13 shows the time history response waveforms (in the Y direction) at the input of the Hachinohe waveform (1968 Hachinohe NS) with the peak ground velocity (PGV) of 25cm/s comparatively for the two base-isolation systems. In the figure, the response displacements of the base-isolation story, the accelerations at the top of the high-rise building, the damping forces of the dampers (a total of five dampers), the control signals to variable oil dampers. Figure 14 shows the damping force vs. velocity

curve of the variable oil dampers. The results of the analyses indicate that the maximum displacement of the base-isolation story of the passive base-isolation system is 9.7 cm, while that of the semi-active base-isolation system is slightly larger, or 10.9 cm. In contrast, the maximum acceleration of the passive base-isolation system at the top of the high-rise building was 92 cm/s^2, while that of the semi-active bas-isolation system is reduced largely to about 74% of the passive base-isolation system, or 68 cm/s^2.

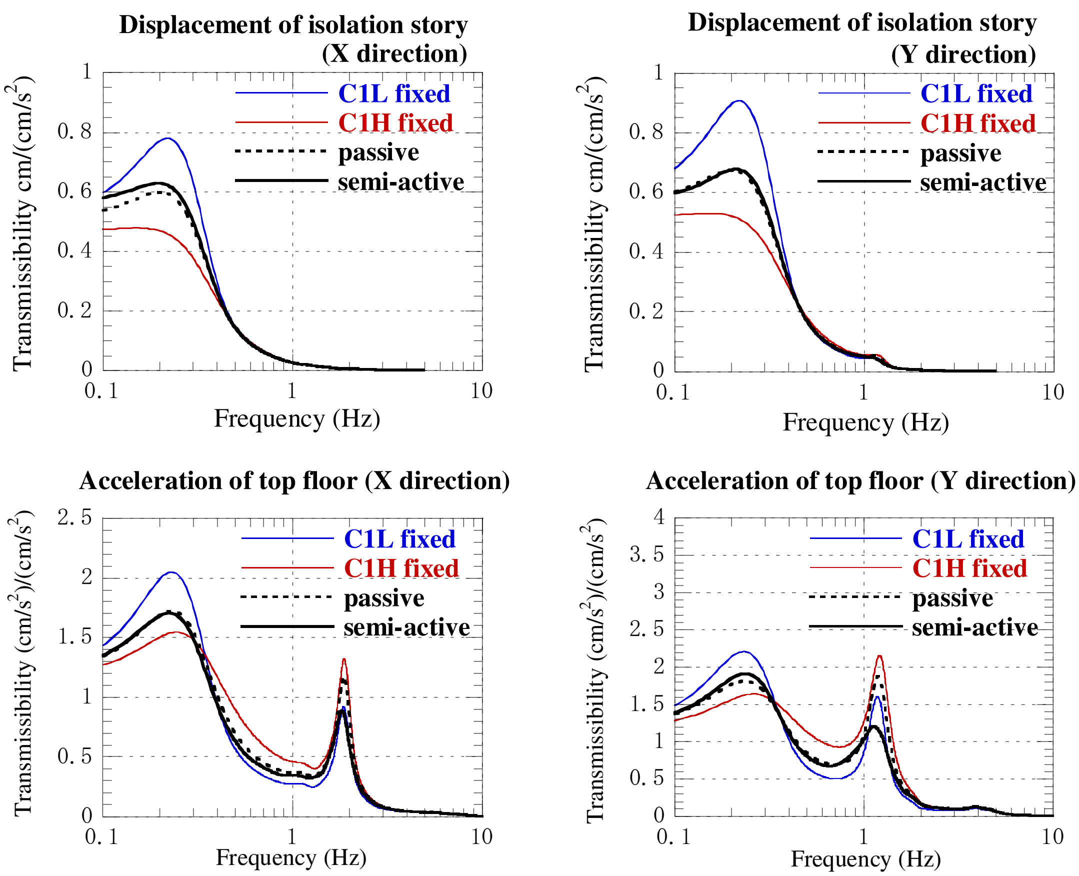


Figure12. Comparison of the Transmissibility between Semi-active and Passive damping system

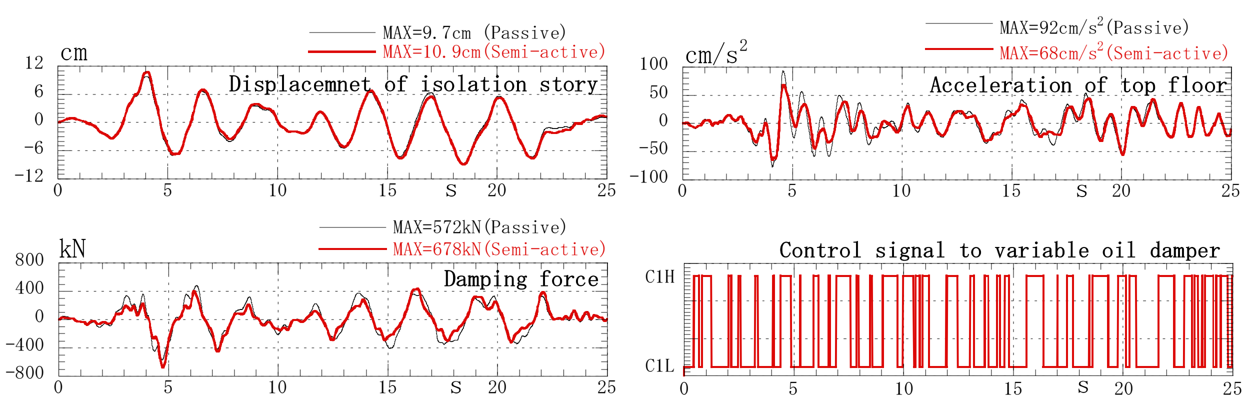


Figure13. Comparison of the Response Waveforms between Semi-active and Passive Damping System (1968 Hachinohe NS with PGV of 25cm/s)

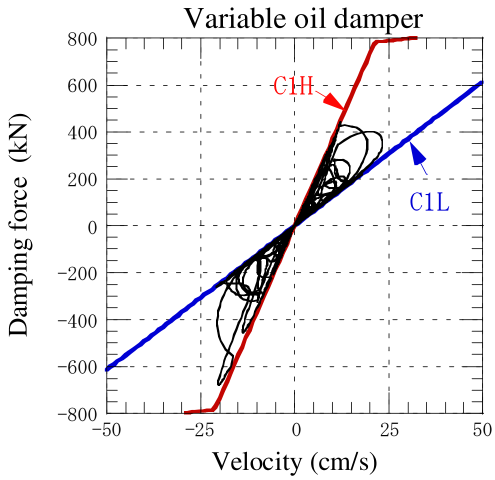


Figure14. Damping Force v Velocity Curve of Variable Oil Damper

CONCLUSION

This paper has demonstrated the superior performance of base-isolated structures, using as an example a base-isolated building with an asymmetrical upper structure. It has also shown an example of the use of a semi-active variable damping system using variable oil dampers.

Base-isolated structure is a technology that not only reduces seismic force and improves structural stability but can also improve the freedom of architectural planning. A rapid increase is anticipated in the number of buildings using seismic isolation structure. However, as yet there are few examples of the use of active, semi-active and other types of control systems to improve the earthquake-resistant safety of buildings, and control objectives, control ranges, methods of use and so on are still at the development stage. In addition, many problems remain to be resolved, such as the use of control content to ensure safety in the event of malfunction, failure or the like. Nevertheless, two desirable performance properties for base-isolated building in the future are (a) control of the displacement of the seismic isolation story in the event of an earthquake motion that is greater than anticipated, and (b) ideal response control with respect to various outside disturbances such as not only earthquake but also wind and environmental vibration. Control systems are crucial for the achievement of these performance objectives. The adoption of the semi-active variable damping system in this project represents the first step toward the introduction of control design to base-isolated structure, and it is hoped that this will lead to further development in the field of base-isolated structure.

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