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High-rise Reinforced-concrete Building Incorporating an Oil Damper in an Outrigger Frame and Its Vibration Analysis

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Abstract

The reinforced-concrete multi-story shear-wall structure, which can free a building from beams and columns to allow the planning of a vast room, has increasingly been used in Japan as a high-rise reinforced-concrete structure. Since this structural system concentrates the seismic force onto multi-story shear walls inside, the bending deformation of the walls may cause excessive deformation on the upper floors during an earthquake. However, it is possible to control the bending deformation to within a certain level by setting high-strength and rigid beams (outriggers) at the top of the multi-story shear walls; these outriggers restrain the bending behavior of the walls. Moreover, it is possible to achieve high energy dissipation by placing vibration control devices on the outriggers and thus restrain the bending behavior. This paper outlines the earthquake response analysis of a high-rise residential tower to demonstrate the effectiveness of the outrigger frame incorporating vibration control devices.

Keywords: High-rise building, Outrigger system, Oil damper, Vibration control, Reinforced-concrete

1. Introduction

In Japan, reinforced-concrete (RC) high-rise residential towers were first built in the 1970s. Structures having purely rigid frames were used at that time with columns having separation of about 6 m connected to main beams in both X and Y directions. The column spacing thus limited the design of a living space (e.g., ceilings were low because of the large beams). In the 1990s, in response to the need for structural systems that allowed more flexible design instead of spatially constrained structures with purely rigid frames, new structural designs appeared. These new structures included those with a tubular frame, wherein columns and beams are arranged as in a colonnade to reduce the number of seismic frames and structures with multi-story shear walls (core walls), where the lateral force acting on the beam-column frames is reduced and, thus, fewer columns and beams are needed. In previous works, we further developed this type of structure with multi-story shear walls at the center of the plan and devised a flexural-deformation-response control system (Omika et al., 2006) as a new concept for a vibration control system using an outrigger system placed at the top of the building (Omika et al., 2000). On the other hand, the Outrigger Working Group of CTBUH developed an outrigger system design guide with an historical overview, considerations for outrigger application, effects on building behavior and design recommendations (Choi and Joseph, 2012).

Our structural system bears all lateral loads resulting from seismic forces and wind forces acting on the core walls (super walls) placed at the center of a floor. The resulting bending deformation of the super walls is transformed into vertical movement of the tips of hat beams (outrigger beams) and then amplified. The amplified displacement activates dampers placed between the tips of the outrigger beams and the tops of outer columns arranged around the exterior of the building (connecting columns) to dissipate vibration energy. In this structural system, each floor is composed of only the super walls, a flat slab and outer columns supporting the axial load from other floors without any other beams connected to the super walls or columns (Fig. 1). This system provides a highly flexible, open and large space that can be used as a residential area.

This report presents an overview of earthquake response analysis on an RC high-rise residential tower equipped with vibration control devices set on the outriggers on the top of super walls; i.e., the flexural deformation response control system.

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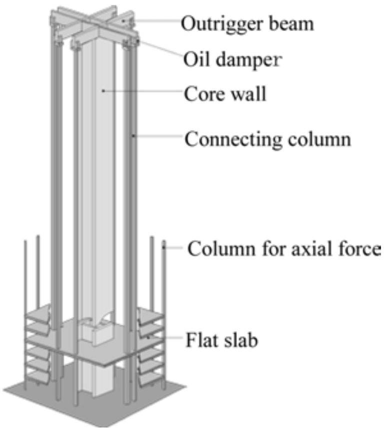


Figure 1. Flexural deformation response control system.

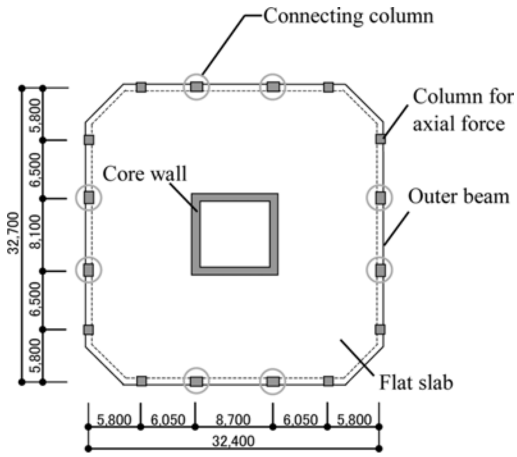


Figure 2. Typical floor plan.

Photo 1. Mark-one Tower Nagatsuta.

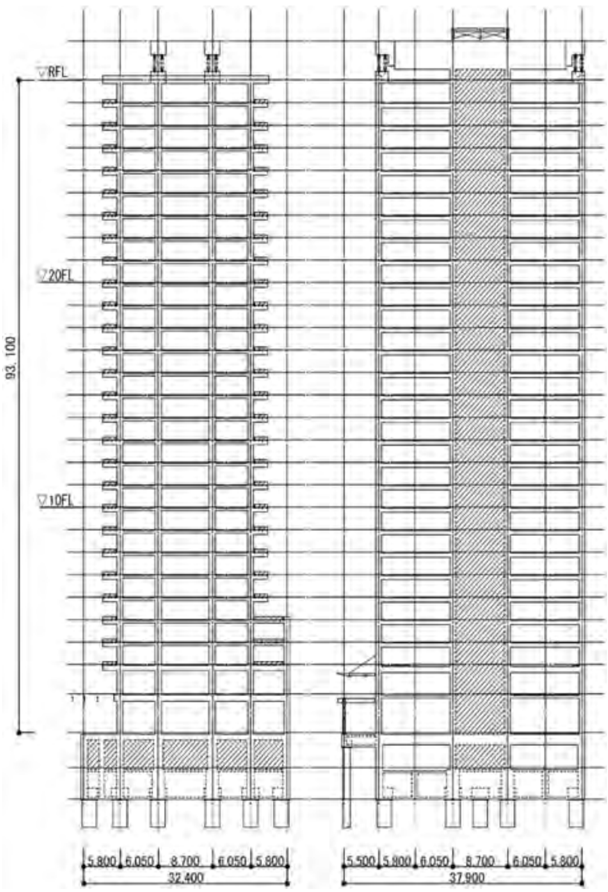


Figure 3. Framing elevation.

2. Structural System of the RC High-rise Residential Tower with Control Devices

The target building is a 29-story, 98.6-m-high RC high-rise residential building that is called the Mark-one Tower Nagatsuta (Owner: Yokohama City Housing Corporation, Design: Azusa Sekkei Co. Ltd. and Kajima Corp., Construction: Kajima Corp. and others) and located in Yokohama near Tokyo as shown in Photo 1. The standard floor plan is shown in Fig. 2. The building has 16 outer columns including eight connecting columns along the perimeter and super walls placed in a square arrangement at the center of each floor. The super walls bear most of the lateral force in each direction. The framing elevations are shown

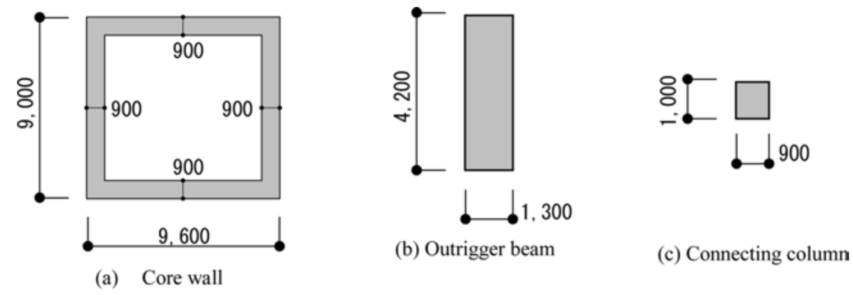


Figure 4. Typical sections of each element.

in Fig. 3.

The super walls have two outrigger beams in each direction at the top. Oil dampers are installed between the tips of the outrigger beams and the tops of eight connecting columns that support the reaction force of the oil dampers. The other columns are placed simply to support the weight of the floors. Three oil dampers are installed at each connecting column, giving a total of 24 dampers.

Cross sections of the super walls, super beams and connecting columns are shown in Fig. 4.

3. Analysis Model

We constructed analysis models according to the following steps. A three-dimensional elasto-plastic frame model is shown in Fig. 5.

1) Beam element models are created for the different structural members; i.e., the super walls, super beams, connecting columns, external frames, and slabs.

2) The nonlinear characteristics of each element given below are considered.

	Bending	Shear	Axial
Walls	Elasto-plasticity (Tri-linear)	Elasto-plasticity (Tri-linear)	Elasto-plasticity
Columns	Elasto-plasticity (Tri-linear)	Elasticity	Elasto-plasticity
Perimeter frames	Elasticity	Elasto-plasticity (Tri-linear)	-
Outrigger beams at the top, Equivalent beam of floor slab	Elasto-plasticity (Tri-linear)	Elasticity	-

3) The vibration control devices, which are the oil dampers, are modelled for installation between the heads of connecting columns and the tips of outrigger beams. The analytical model of the vibration control device is described in detail in section 4.

4) The degrading trilinear hysteretic loop proposed by

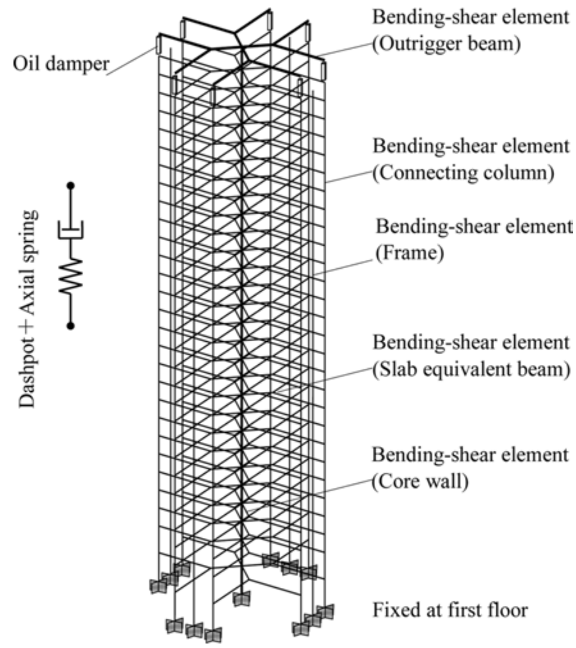
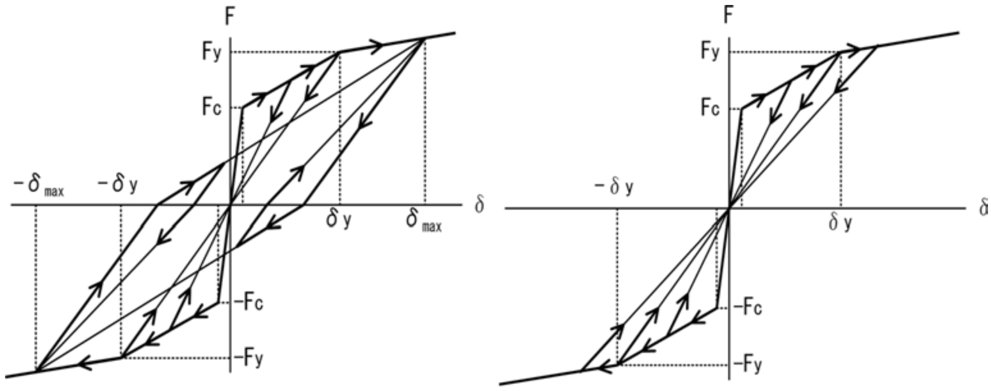


Figure 5. Response analysis model.

Dr. Muto is introduced for the evaluation of the bending and shear characteristics of the super walls, the bending of the connecting columns and outrigger beams and the shear of the perimeter frames based on the trilinear skeleton curve.

5) The overall model is created so that the super walls, connecting columns and outer perimeter frames are connected by a rigid floor at each floor and further outrigger beams and damping devices are included.

6) The computer code Fappase, developed by Kajima Corporation, is used for analysis. This is a generic nonlinear analysis code that has three rotational degrees of freedom and three translational degrees of freedom at each node. This code can handle several elements, such as a three-dimensional non-linear beam, non-linear truss, nonlinear spring, non-linear dashpot, non-linear beam-column joint panel, linear shell and linear soil spring. In this program, each node has degrees of freedom of translation in two directions, in-plane rotation, vertical translation and



(a) Degrading Tri-linear model (b) Origin oriented model

Figure 6. Hysteresis loop.

out-of-plane rotations in two directions.

7) Rayleigh's damping is assumed for the damping of the structure. The damping factor is set as 0.03 for the first natural period, which is the first vibration mode in the Y direction, and the fifth natural period, which is the second vibration mode in the X direction, and a damping matrix is configured in proportion to the initial stiffness matrix.

8) The analysis model is fixed at the ground floor, and the assumed ground motion for design is input to the ground floor level.

4. General Description of the Vibration Control Device

The vibration control device installed in the building is composed of elements such as a cylinder, piston, piston rod, control valve, relief valve, and accumulator. The cylinder is filled with oil, which generates a damping force through its resistance when passing through the valve. The control device has the damping characteristic that the damping force becomes bilinear through the operation of the relief valve, which is referred to as a relief force. A dimensional drawing of the device is shown in Fig. 7. The device is attached to the structure using a ball joint provided at the end of the cylinder and the piston rod. Because only an axial force acts on the device, this ball joint has a structure that can rotate within an angle of 5 degrees freely in any direction except the axial direction.

The dynamic behavior of the device is explained as a Maxwell model with a dashpot and a spring placed in series, where the damping constant C is derived from pressure-flow rate characteristics of the oil passing through each valve; and the spring constant K is derived from the compression property of the inner sealed oil and the device stiffness, including the characteristics of the clevis. The relief force is 1600 kN. The velocity-force relationship of the dashpot is shown in Fig. 8.

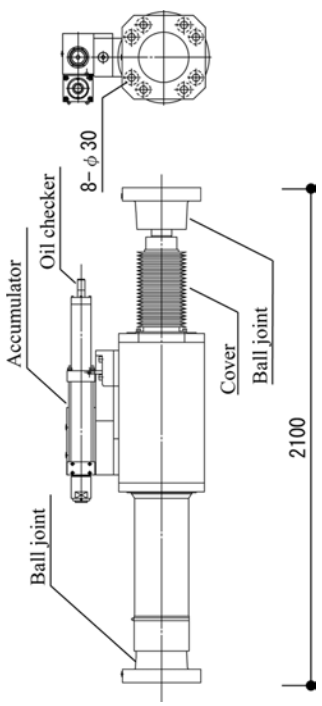


Figure 7. Overview of control device.

5. Results of Seismic Response Analysis

5.1. Input earthquakes

Input earthquakes for seismic response analyses are enlarged artificial ground motions based on earthquake motions that occur very rarely as defined by Japanese building law. We adopted three artificial earthquake motions, each having a different phase, whose peak values of the velocity response spectrum under a damping factor of 0.05 are increased to 100 cm/s. Our design criterion in these analyses is that the maximum story drift angle of each floor is less than 1/100.

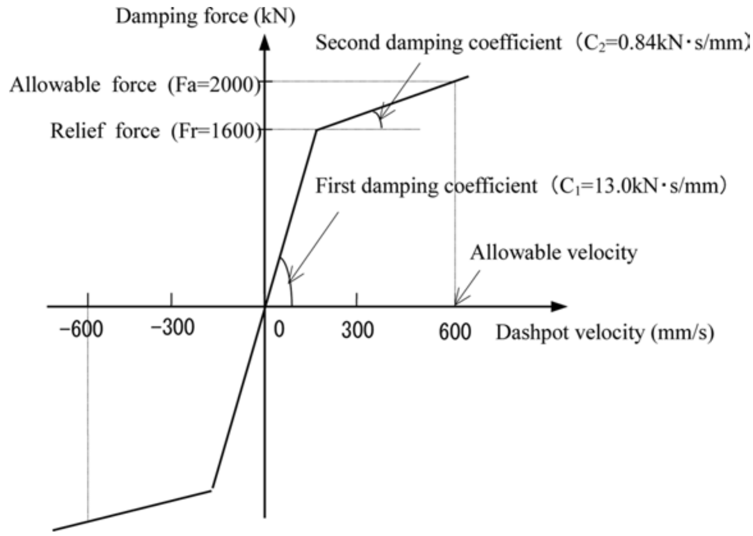


Figure 8. Velocity-force relationship of dashpot.

Table 1. Natural periods

Direction	X direction (sec)			Y direction (sec)		
Mode	1st	2nd	3rd	1st	2nd	3rd
Natural period	2.74	0.57	0.23	2.82	0.59	0.24

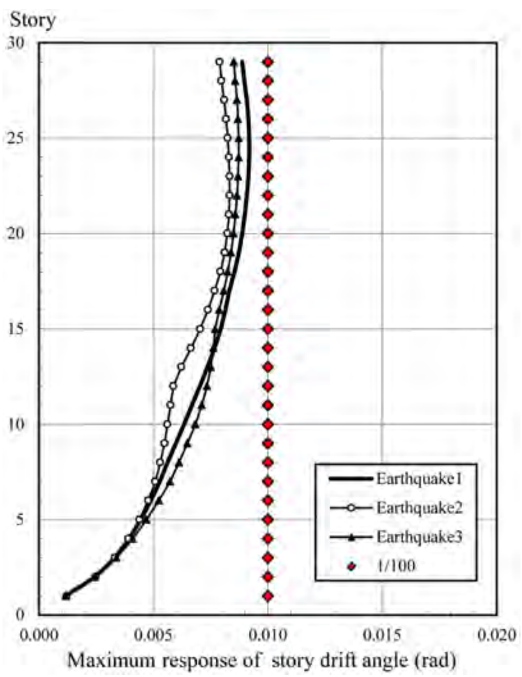


Figure 9. Maximum response of story drift angle (Controlled condition).

5.2. Analysis result

The results of eigenvalue analysis are given in Table 1. Representative results of the seismic response analysis for the X direction are shown in Fig. 9.

For Level-2 design earthquakes, which are the strongest earthquakes considered under the Japanese building code, the maximum value of the maximum response of the story drift angle is 1/109 in the case of an artificial earthquake with Rinkai phase, which is within the criterion of 1/100. Additionally, it was confirmed that the bending and shear response of a super wall have safety margins of at least 0.5 times each ultimate strength.

For the response of the seismic control dampers, it was confirmed that the maximum response velocity was 570 mm/s, which is within the allowance of 600 mm/s; and the maximum response stroke was 99 mm, which is within the allowance of 200 mm. Time histories of the energy consumption of each component for the Level-2 design earthquake are shown in Fig. 10. The figure shows that 58% of all energy is consumed by the oil dampers, which make a great contribution to the reduction of the building response.

5.3. Analysis results under different connection conditions at the position of installation of devices

Fig. 11 shows the results of analysis in two other cases. One is the case that the control devices are removed from the installation position between the tip of an outrigger beam and the top of a connecting column, referred to as the free condition, and the other is the case that the outrigger beam and connecting column are rigidly connected without the devices, referred to as the fixed condition. Fig.

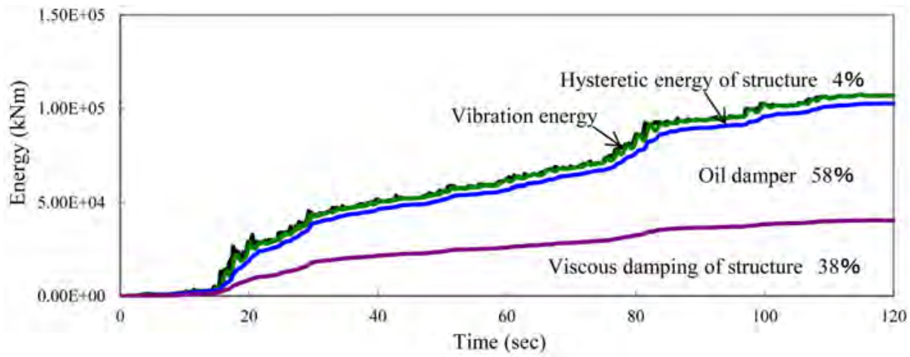


Figure 10. Energy absorption time history (Controlled condition).

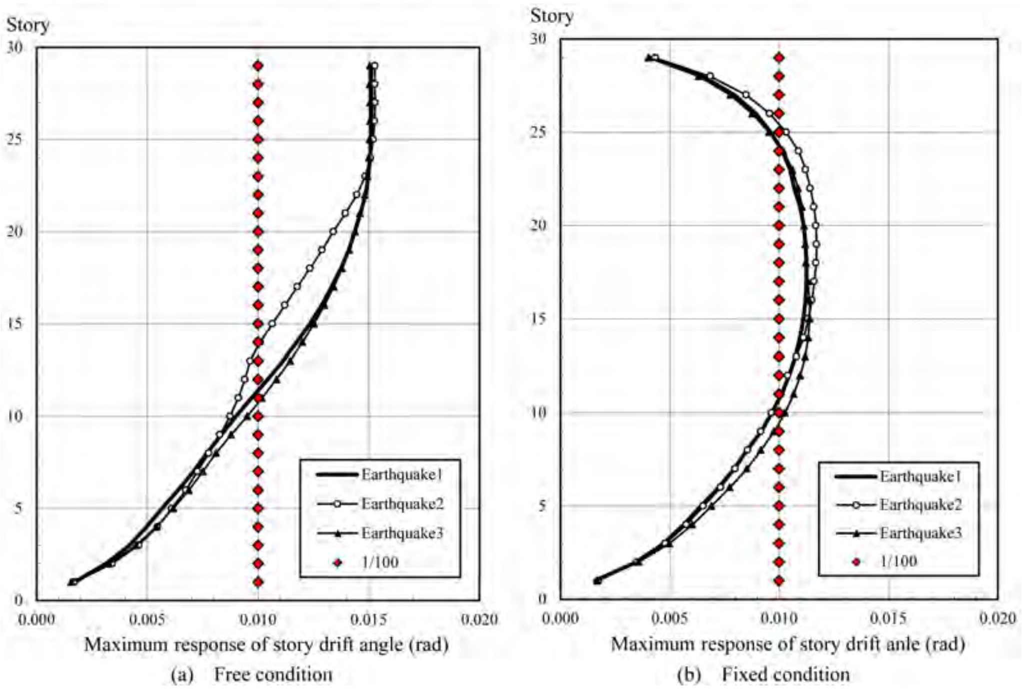


Figure 11. Maximum response of story drift angle.

12 compares the maximum stresses generated in connecting columns in three different cases: the two cases described above and the case that the control devices are installed, referred to as the controlled condition (see section 5.2).

The maximum response value of the story drift angle is 1/65 for an artificial earthquake with random phase under the free condition, and 1/85 for the same earthquake under the fixed condition. In the case of the fixed condition, excessive stresses of an axial force of about 15,000 kN and bending moment of about 30,000 kN-m are generated at the top of the column, where it is connected to an outrigger beam. It is presumed that the design of the element would be impossible or the portion would be severely damaged in this case. Meanwhile, under the controlled condition, the stresses of column members are an axial force of about 6000 kN and bending moment of about 800 kN-m owing to the control by the oil dampers, and these values remain within possible design ranges. Under the free condition, naturally, the stresses are lowest in all three cases.

Fig. 13 shows time histories of energy consumption of each component for the artificial earthquakes. Under both free and fixed conditions, more than 80% of total energy absorption is due to viscous damping of a structure since there is no contribution from the dampers.

6. Conclusion

The results obtained in the present study verify the effec-

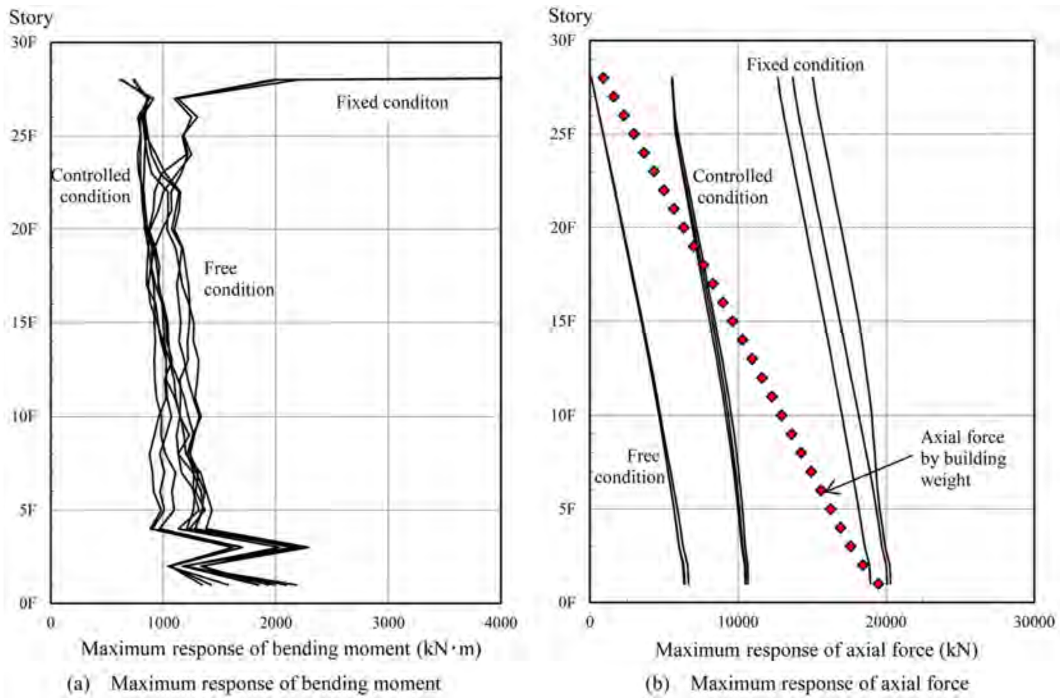


Figure 12. Comparison of stressed of connecting column.

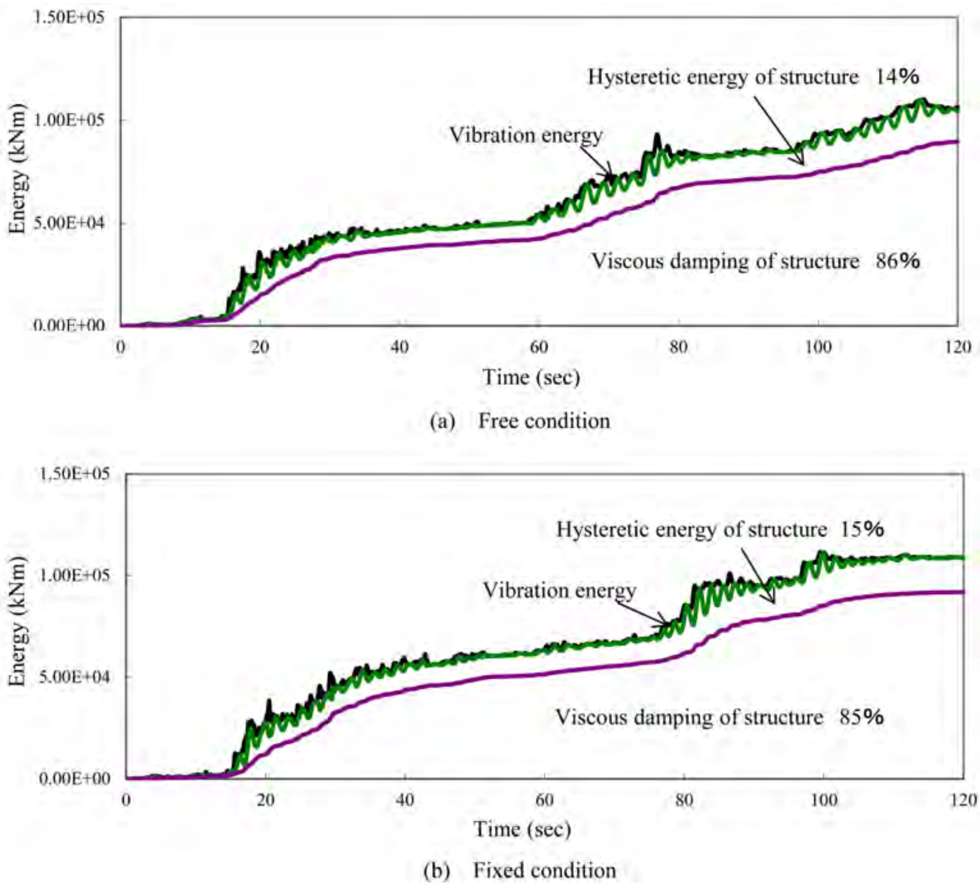


Figure 13. Energy absorption time histories of each element.

tiveness of the oil damper as a vibration control device. The device installed at the tip of an outrigger beam works well to control vibration by absorbing enough energy efficiently and by restraining bending of the core wall when the outrigger system is adopted to control the bending deformation of the core wall.

This paper mainly reported an outline of the earthquake response analysis of a high-rise residential tower to demonstrate the effectiveness of the outrigger frame using the flexural deformation response control system. This system has been adopted in 14 RC high-rise residential towers so far.

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