Feasibility Study of Response Controlled Structure with Eccentric Core and Damper Tube System

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SUMMARY:
This paper proposes a new structural control system utilizing torsional vibration consists of an eccentric core, flexible perimeter frames with pin-jointed post-columns that support only vertical loads, slab elements and energy dissipation devices (dampers) installed in the perimeter frames. Inputted seismic energy is converted into torsional vibration energy, and the dampers effectively absorb the energy utilizing the torsional vibration, which is usually avoided in seismic design. This system is nicknamed "Damper Tube Structure". In spite of the simplicity, this system has robustness and redundancy against the design parameter's fluctuation and the earthquake levels. Moreover, the deformation of the core can be kept small and the perimeter frames are pin-jointed flexible structures, a building with no damage can be easily realized even in severe earthquakes. These features are discussed through the design example of high-rise building, and the newly developed oil damper for this system is also presented in this paper.

Keywords: Structural Control, Torsional Vibration, Energy Absorption, Oil Damper, Robustness

1. INTRODUCTION

This paper proposes a new structural control system that realizes substantial earthquake response reduction utilizing torsional vibration. it consists of an eccentric core structure, flexible perimeter frames with pin-jointed post-columns that support only vertical loads, slab elements that transmit the shear force between the core structure and the perimeter frames, and energy dissipation devices (dampers) installed in the perimeter frames diagonally like a net. Inputted seismic energy is converted into torsional vibration energy due to the eccentricity of the core structure, and the dampers arranged in the perimeter frames effectively resist and absorb the energy utilizing the torsional vibration, which is usually avoided in seismic design. This system is nicknamed "Damper Tube Structure". In a country subject to severe earthquakes like Japan, the size and strength of the structural members are usually determined by the horizontal loads due to earthquakes. In the proposed structure, however, horizontal load is important only for the core structure, and we can focus on the vertical loads in designing the perimeter frames. This makes the architectural design as well as structural design simple and free.

It should be mentioned that in spite of the simplicity of the structural construction, the structure with this system has robustness and redundancy against the fluctuation of the design parameters such as a change of eccentricity and a level of input earthquakes because when the perimeter frames' displacement becomes larger due to torsional vibration, the efficiency of the dampers increase. Moreover, the deformation of the core structure can be kept small because of the feature of the torsional vibration, and because the perimeter frames are pin-jointed flexible structures, buildings with no damage can be easily realized even in severe earthquakes.

In this paper, we first outline the concept of this new structural system. Next, we discuss the features and advantages of the proposed system through the design example of high-rise building. We also demonstrate the experimental results of the newly developed oil damper with slender shape and high performance designed to meet the needs of this system.

2. CONCEPT OF DAMPER TUBE STRUCTURE

The concept of the Damper Tube Structure (DTS) is "a structure of free-planning, low-stiffness and greatly response controlled". In this system, though the core structure is the only stiffness element that resists static horizontal load, its arrangement in the plan is permitted to be free to ensure high planning flexibility. The other frames, including the perimeter frames, are designed as flexible structures such as pin-jointed post-columns that support only vertical loads. Compared with conventional seismically designed structures, the DTS has low stiffness and large eccentricity because the stiffness element is only the core structure, and its arrangement is permitted to be free. Thus, we introduce energy dissipation devices (dampers) into the perimeter frames diagonally like a net to control horizontal, torsional and vertical vibration. The slab of each floor is an important structural element that transmits shear force between the core structure and the perimeter frames. Fig. 1 shows a conceptual diagram of the DTS.

The response displacement of the core structure can be kept small because of the feature of the torsional vibration, and because the perimeter frames are pin-jointed flexible structures, a building with no damage can be easily realized even in severe earthquakes. In addition to the attractive features from the viewpoint of seismic design, there is a possibility of realizing a new architectural design in countries like Japan that are subject to severe earthquakes because the arrangement of the core structure is free and the connection of the other frames and slab elements can be simple pin-jointed.

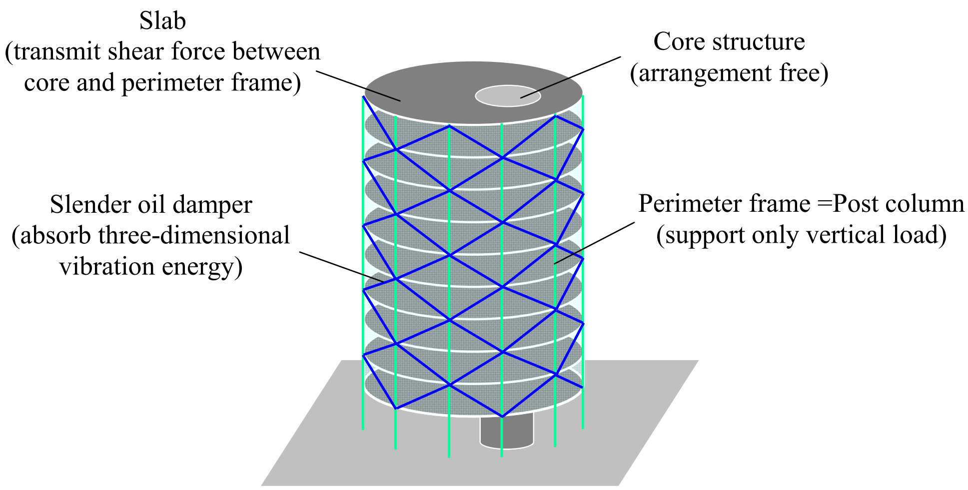


Figure 1. Conceptual diagram of Damper Tube Structure

3. INPUT EARTHQUAKES AND CRITERIA

DTS is based on an entirely new concept. It is designed to intentionally induce torsional vibration and to absorb seismic energy with dampers. Although the system's feasibility has been proved using a simple numerical model [Kurino and Kano 2012], here we decided to set up more severe criteria to give it a much higher seismic margin, considering its simplicity as well as its originality.

Fig. 2 shows the target acceleration spectrum of the design earthquake (h=5%) defined in the Japanese code, and Table 1 summarizes the criteria we set up for DTS. For comparison, Table 1 includes the conventional criteria for buildings over 60m high in Japan. For DTS, we fix the criteria for a level 2 earthquake (L2): story drift angle ratio less than or equal to 1/120 and ductility factor of members within the elastic region. We can thus ensure a building's robustness against repeated aftershocks after a severe earthquake. We also fixed the criteria for a level 3 earthquake (L3) as 1.5 times L2, which is undefined in the Japanese code: story drift angle ratio less than or equal to 1/75 and ductility factor of members less than or equal to 4.0. These criteria enhance the seismic margin of a building and, even if the building is exposed to an unexpectedly large earthquake, they can prevent finishing materials such as facades from falling off, and obviate the need for large-scale building repairs.

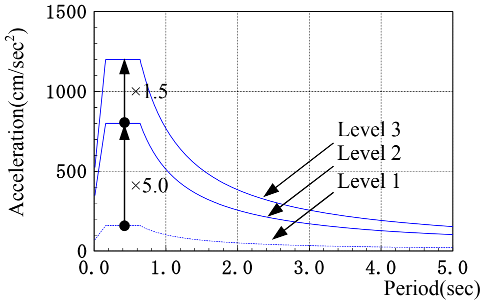


Figure 2. Acceleration spectrum of input earthquakes(h=5%)

Table 1. Criteria for earthquakes

Input level	Check items	Conventional design (Japan Code)	Damper Tube
L2	Story drift angle ratio	≦ 1/100	≦ 1/120
	Ductility factor	≦ 4.0	≦ 1.0
L3	Story drift angle ratio	-	≦ 1/75
	Ductility factor	-	≦ 4.0

4. DESIGN EXAMPLE

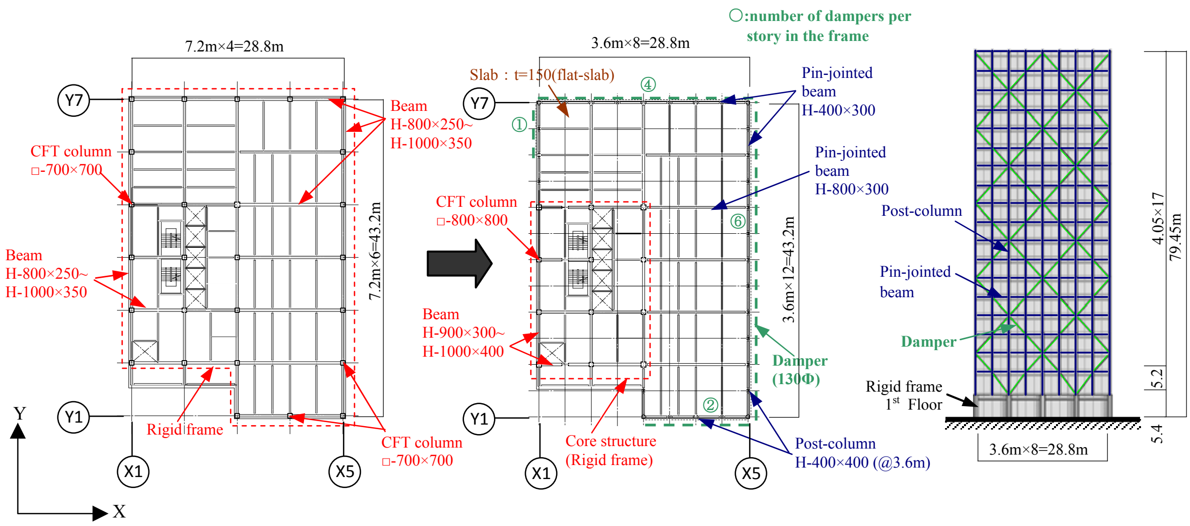
In this chapter, we first show a typical design example with particular DTS characteristics. Because DTS has unique structural features, various points must be carefully considered in its design, and these points are pointed out. Next, we clarify the feasibility of DTS by conducting seismic response analyses using precise vibration model. In this study, we not only ensure that the analysis results meet the criteria, but also clarify the various advantages of DTS, such as high robustness against various factors, decrease of acceleration as for a seismic isolation structure, and so on. Finally, we confirm the specifications required for the oil damper, which is an essential element of DTS.

4.1 Outline of Building

The building of the design example has 19 floors above ground, and is used as offices. Fig. 3(a) shows a framing plan for a conventional design based on the Japanese code. Rigid frames are arranged as evenly as possible to minimize eccentricity and thus torsional vibration. As a result, the size and strength of the structural members is increased on average over the entire building. However, when we design the same building as DTS, we obtain a framing plan and an elevation as shown in Fig. 3(b), (c), respectively. This building has very characteristic appearance with many dampers arranged diagonally in the perimeter frames: 13 per floor and 234 in all. Moreover, we limit the rigid frames in the core structure to 1/4 of the entire plan and arrange them eccentrically in order to induce torsional vibration, contrary to the previous case, and to utilize the dampers effectively in the perimeter frames. Besides, by matching the position of the core structure to that of the architectural core, we can design the architectural plan more freely without being affected by the structural plan.

In DTS, we intentionally made the members of core structure bigger than those of the conventional design to consider both fluctuation of axial force in the columns in the core structure and the influence of shear force in the orthogonal direction, as well as to increase the building's stiffness . This does not mean that seismic forces generated in the core structure are increased. On the contrary, we can control the seismic shear force of the columns in the core structure to be the same as that of the conventional design structure in spite of the decreased number of rigid frames, because the seismic shear force generated in the entire structure can be reduced dramatically due to the decrease of acceleration, and deformation of the core structure can be minimized due to the torsional vibration feature. This is clarified in a later section. By contrast, we can reduce the sections of columns in the perimeter frames, which are determined only from the long-term vertical loads. This is because we devise the structure of DTS so as to generate negligible axial force in the columns of the perimeter frames, by making all beams pin-jointed except a core structure, and by arranging the dampers in the perimeter frames continuously and symmetrically. In addition, we can reduce the amount of welding by making all the beams except the core structure pin-jointed, and we can expand the use of H-shaped steel sections of JIS standard, which are widely used and cheap in Japan. As a result, we can design DTS structures economically, even taking into account the cost of the dampers, if the building is large-scale as in this design example.

Furthermore, the following must be mentioned as an important point in DTS design. First, we must ensure that the seismic shear stress in the slab does not reach shear yield, because if it does, and the core structure and the perimeter frames moved separately, DTS will not work at all. Next, due to the relatively small stiffness caused by the limited core structure, we need to consider deformation and vibration against wind load. In this design example, the maximum story drift angle ratio against level 2 wind load defined in the Japanese code is about 1/290, and we can say that this value is safe enough because it is less than 1/120 and within the elastic region, which are criteria for L2 earthquakes. Meanwhile, we can control vibration against wind load owing to the high damping effect, and thus realize high building habitability. Finally, we must carry out two operations to improve freedom of architectural design: to not locate dampers on the first floor, and to develop a new oil damper designed as a part of the exterior design of the building. This damper looks like just a steel pipe with diameter 130mm with no obstacle on it. As shown in a later section, this oil damper has not only a slender shape but also a high performance specification. It can work effectively with no mechanical gap under very small vibration caused by wind as well as under very large vibration caused by earthquake.

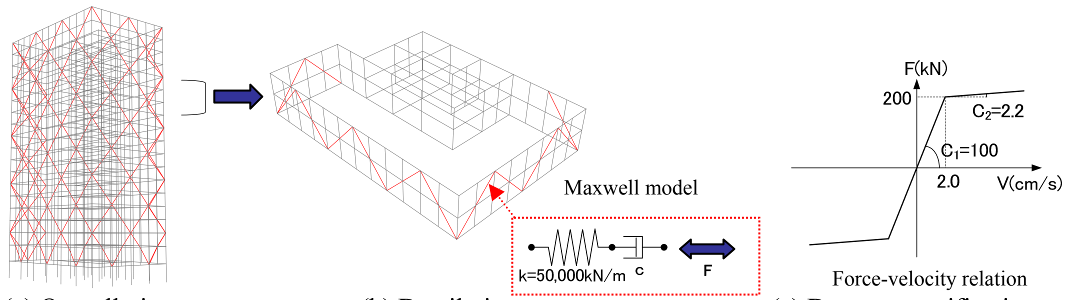


(a) Framing plan(Seismic Design) (b)Framing plan(DTS) (c)Y7 Elevation(DTS)

Figure 3. Drawings of building

4.2 Analytical Model

Fig. 4 shows the vibration model used for seismic analysis. It is a three dimensional precise model consists of each elements such as columns, beams, connection panels and dampers. The column portion is substituted by a wire model, and bending, shear and axial deformation are taken into account. The beam portion is also substituted by a wire model, and bending and shear deformation are considered. Besides, in the beam portion, the moment-rotation angle characteristic is set to a normal bi-linear curve with the break point fixed at the full plastic moment. The panel portion is modeled by a plate, and shear deformation is considered. The damper portion is expressed as a Maxwell model with the force-velocity characteristic shown in Fig. 4(c). We determined those specifications from two conditions: all oil damper components are housed in a slender pipe, and the damper has sufficient stiffness for it to work stably without flexural deflection under compression. These specifications are the same as for specimen L140 in the experiment, which is described in a later section. In addition, we assume the column base on the first floor to be fixed, each floor to be rigid, and the structural damping ratio to be 2%.



(a) Overall picture (b) Detail picture (c) Damper specification

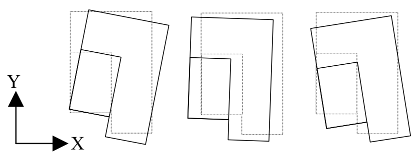
Figure 4. Analytical model (DTS)

The eccentricity ratio and the spring force ratio of this model are $\bar{e}_x$=0.37, $\bar{e}_y$=0.28, $\bar{j}_x$=0.73, $\bar{j}_y$=0.87 respectively. According to the fundamental study [Kurino and Kano 2012], optimum damper distribution ratio α is approximated by $\alpha_{opt} = 2\bar{e} + 2\bar{j} - 1.8 \;\; (0 \le \alpha_{opt} \le 1)$. Substituting $\bar{e}$, $\bar{j}$ into the formula, α is estimated as α_x=0.5, α_y=0.4. These values indicate that the optimum damper arrangement for this building is with dampers placed evenly in opposite frames in both directions. In this paper, the study is conducted mainly under the damper arrangement shown in Fig. 3(b) (α_x=0.67, α_y=0.86). We consider this arrangement in the seismic response analysis in a later section.

Table 2 summarizes the model's natural periods and mode shapes. For comparison, Table 2 includes the natural periods of the conventional design model. For DTS, the first and third modes are torsional and the second mode is sway. We also conducted complex eigenvalue analysis, and got high damping ratios of 17.6% (1st), 6.6% (2nd), and 5.5% (3rd), respectively, as we expected, when the damping ratio of the structure was 2%.

Table 2. Natural period (Sec)

Mode	Conventional design	Damper Tube
1^{st}	2.48 (Xdir)	4.13
2^{nd}	2.25 (Ydir)	2.98
3^{rd}	1.93 (Torsion)	2.27



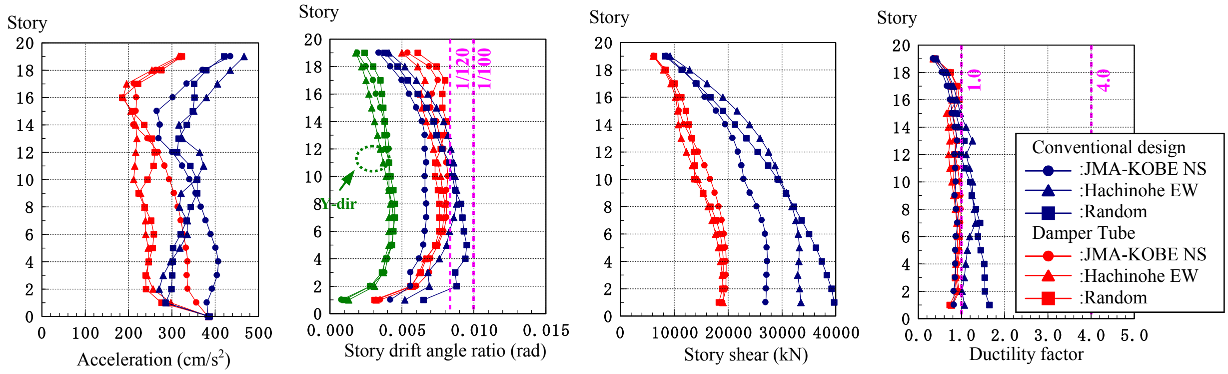
(a) 1^{st} mode (b) 2^{nd} mode (c) 3^{rd} mode

4.3 Seismic Response Analysis

In order to examine the dynamic characteristic of DTS, we conducted seismic response analyses for three earthquakes with different phases and the spectral characteristic is shown in Fig. 2. We describe the results of the analyses in the following. In this paper, we focus on only L2 and L3 earthquakes.

4.3.1. Comparison with conventional design model

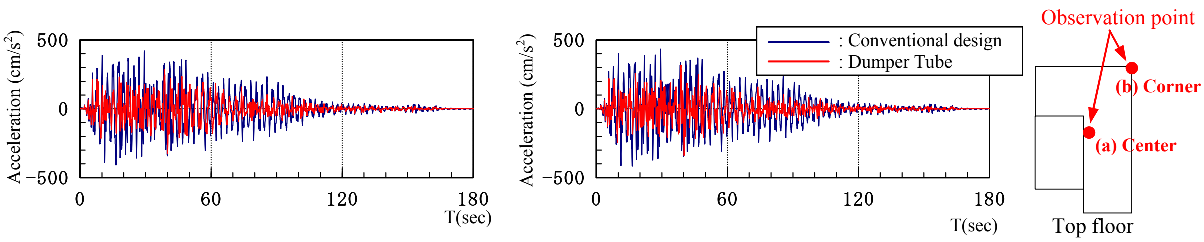
Fig. 5 shows the maximum response distribution against the L2 earthquake input in the X-direction. It includes the results of the conventional design model for comparison. Compared with the conventional design model, the results of the DTS model have following characteristics: 1) acceleration is about 20-40% smaller, 2) story drift angle ratio is almost equal (story drift angle ratio in Fig. 5(b) shows maximum value of four perimeter frames), 3) story shear force is approximately half, and 4) story drift angle ratio and ductility ratio satisfy the criteria shown in Table 1. In addition, the variation of these results for earthquakes with different phases is smaller than that of the conventional design model owing to the high damping ratio. Fig. 5(b) also shows the maximum story drift angle ratio in the Y-direction according to the DTS model. We can confirm that the maximum value reaches about 1/200 due to torsional vibration.



(a)Acceleration (b) Story drift angle ratio (c) Story shear (d) Ductility factor

Figure 5. Maximum response for level 2 dynamic analysis

Fig. 6 compares the time histories of acceleration during the earthquake on the top floor for the DTS model and the conventional design model. We measure them not only at the center of the plan where the influence of the torsional vibration is small, but also at the corner where the acceleration of DTS is amplified by the torsional vibration. We can confirm that the acceleration for DTS is greatly reduced for all durations at both points.

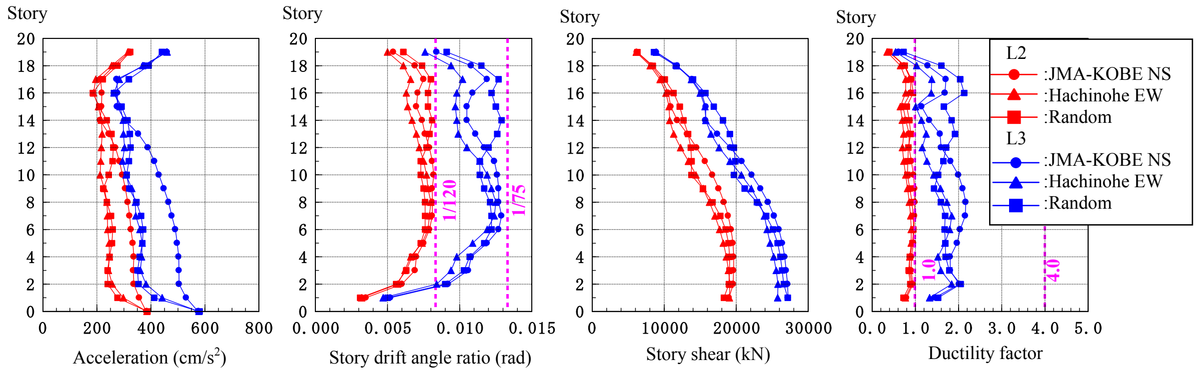


(a) Center (b) Corner

Figure 6. Time history of acceleration for level 2 dynamic analysis (Random)

4.3.2. Comparison by input level of earthquakes

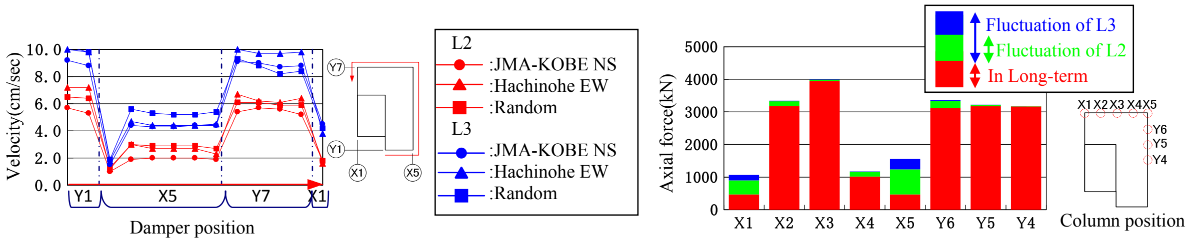
Fig. 7 shows the maximum response distribution of the DTS model against L2 and L3 earthquakes input in the X-direction. We can confirm that story drift angle ratio and ductility ratio satisfy the criteria shown in Table 1, and the variation of these results against earthquakes with different phases is still small against L3 earthquakes.



(a)Acceleration (b) Story drift angle ratio (c) Story shear (d) Ductility factor

Figure 7. Maximum response for dynamic analysis (L2, L3)

Fig. 8 shows the maximum response velocity of the oil dampers and the maximum response axial force of the columns (maximum of 3 earthquakes) in the perimeter frames at the representative floor. Force application conditions are the same as above. As shown in Fig. 8(a), maximum velocities against L2 and L3 earthquakes reach about 7cm/sec and 10cm/sec, respectively, and the dampers in the Y-direction frame are also beyond the relief velocity of 2cm/sec. From Fig. 8(b), we can see that the seismic axial force is much smaller than the long-term axial force except in the corner columns.

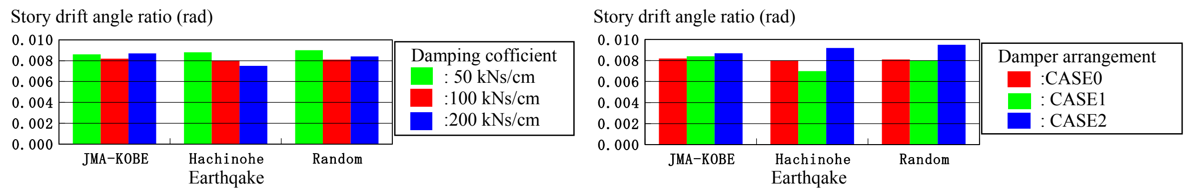


(a) Maximum response of oil damper (10F) (b) Axial force fluctuation of the columns (10F)

Figure 8. Maximum response for dynamic analysis (L2, L3)

4.3.3. Influence of damper specifications and damper arrangement

Fig. 9 shows the maximum story drift angle ratio, which is the maximum value for all floors and all frames, against the L2 earthquakes input in the X-direction. In Fig. 9(a), we examine the influence of the damping coefficient of the dampers by varying it from the standard value of 100kNs/cm shown in Fig. 4(c), to 1/2 (50kNs/cm) and to 2 times (200kNs/cm). Despite the great difference of up to 4 times between the damping coefficients, we see hardly any difference between the results. In Fig. 9(b), we examine the influence of damper arrangement. For this purpose, we change the arrangement of the dampers from the standard case (shown in Fig. 3(b) = Case0) to the optimum arrangement case in which the dampers are arranged evenly in opposite frames by doubling the dampers in Y1 frame (= Case1), and to the reduced case in which only 10 dampers in Y7 and X5 frames are left in every story (= Case2). Story drift angle ratio for Case0 is almost equal to that for Case1. Meanwhile, for Case2, it is bigger than those in other two cases. Therefore, we can confirm that an optimum arrangement is not necessarily required, but the dampers should be arranged in opposite frames as much as possible.

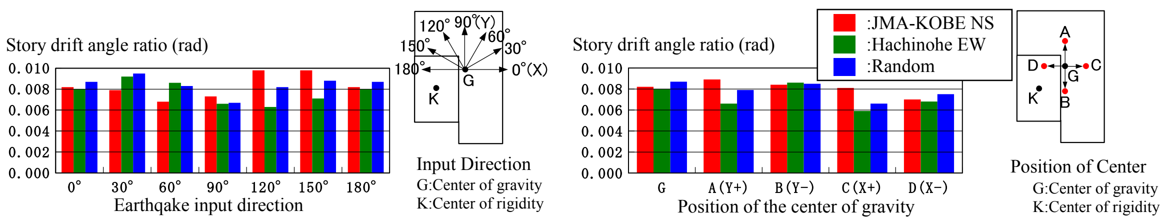


(a) Influence of damping cofficient (b) Influence of dampers' arrangement

Figure 9. Maximum response for level2 dynamic analysis

4.3.4. Confirmation of robustness

Fig. 10 shows other study results against the L2 earthquakes. For Fig. 10(a), we changed the earthquakes' input direction in 30 degree steps from 0 degrees (= X-direction) to 180 degrees. The variation of story drift angle ratios against the input directions is within the expected range and they satisfy the criteria generally. For Fig. 10(b), we changed the position of the center of gravity in all floors by plus or minus 5% for the length of the plan (X-dir is ±1.44m and Y-dir is ±2.16m), which is large enough for buildings not usually considered. Despite this extreme assumption, we can confirm that the story drift angle ratios fluctuate little. Thus, DTS has high robustness against various factors.



(a) Influence of input direction (b) Influence of center of gravity

Figure 10. Maximum response for dynamic analysis

5. EXPERIMENT OF NEWLY DEVELOPED OIL DAMPER

In this chapter, we demonstrate experimental results of the newly developed oil damper with slender shape and high performance designed to meet the needs of this system. In addition, we compare a simulation result with an experimental result and thus prove that we can accurately simulate the behavior of this oil damper.

5.1 Method of Experiment

Fig. 11 shows the newly developed damper consisting of an oil damper portion and a steel pipe portion. The oil damper portion is 740mm long and 120mm in diameter, and houses a piston, a rod and an accumulator. The steel pipe portion is a commercial item, but it has very important roles: to give the damper sufficient stiffness to work stably under compression, and to provide higher buckling resistance than the maximum damping force of the damper. Finally, the oil damper portion is covered with a finishing pipe with the same diameter as the steel pipe portion, with no obstacle on it. As a result, it has the overall appearance of a slender steel pipe. From the viewpoint of maintenance after construction, we can examine whether it is in operation or not by checking the oil level externally.

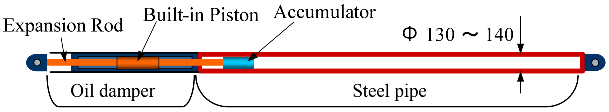
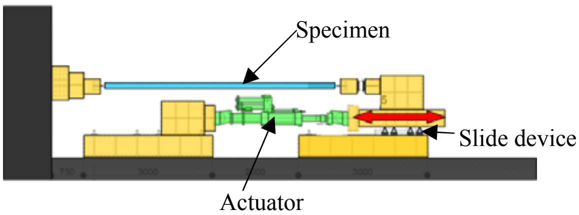
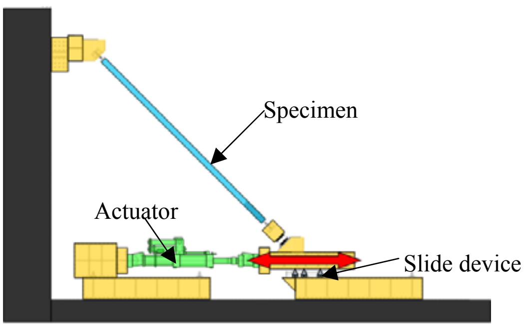


Figure 11. Section of damper

We carried out the dynamic loading tests with this slender damper to verify its stability against flexural buckling and its high performance under several conditions. Table 3 summarizes the properties of the two specimens with different lengths and cross sections of the steel pipe portion and specifications of the oil damper portion. Two different loading conditions were adopted, as shown in Fig. 12(a) and (b). Fig. 12(c) shows a picture of the diagonal loading frame. The diagonal case is tested in order to consider the state of actual use in the building.



(a) Horizontal loading frame



(b) Diagonal loading frame

(c) Diagonal loading frame(S130)

Figure 12. Configuration of loading frame

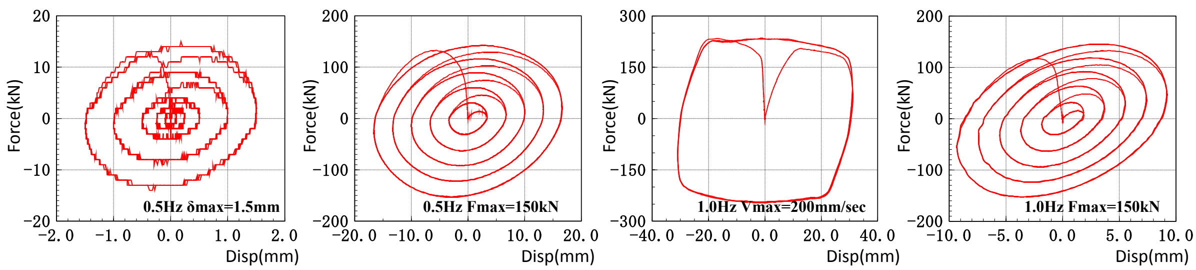
Table 3. Properties of specimen

	Oil damper portion				Steel pipe portion	Total length (m)	Euler buckling Load (kN)
	C1 (kNs/cm)	C2 (kNs/cm)	Rilief force (kN)	Limit force (kN)			
S130	30	2.7	200	250	Φ130×10	5.5	442
L140	100	2.2	200	250	Φ140×12	7.5	349

We carried out sinusoidal loading tests to confirm the basic characteristics of the damper, and random loading tests to confirm the stability and durability under long-time loading. In the sinusoidal loading tests, we selected three different excitation force levels named "Small", "Middle" and "Large". "Small" is the case assumed the vibration under the wind load, and the loading amplitude is less than or equal to 1.5mm. "Middle" is under the relief force of the damper (target damping forces are 30, 60, 90,120, and 150kN) and excitation frequencies are 0.25, 0.3, 0.5, 1.0, and 2.0 Hz. "Large" is over the relief force of the damper and excitation velocities are 5, 10, 15, 20, 25cm/sec with frequency of 1.0Hz. In random loading tests, we used the story drift time histories obtained from the seismic response analysis in the previous chapter as input waves.

5.2 Result of Experiment

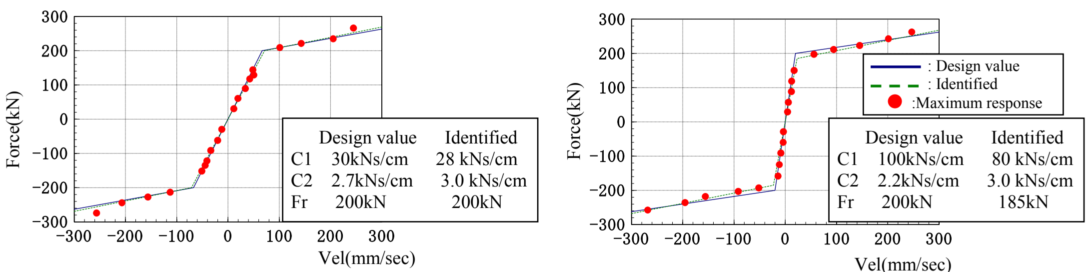
Fig. 13 shows typical force-displacement relations of S130. Force and displacement in the diagonal loading case are converted to the axial direction of the damper. We can confirm that the damper demonstrates consistent performance as we expected. It should be noted that L140 showed stable results as well.



(a)Small(Horizontal) (b)Middle(Horizontal) (c)Large(Horizontal) (d)Middle(Diagonal)

Figure 13. Force-displacement relation of under harmonic excitation (S130)

Fig. 14 shows the force-velocity relations for both specimens. Plots show the maximum values in the experiments, the block line indicates the target specification, and the dotted line indicates the identified specification. We can confirm that the dampers demonstrated the expected performance in all areas in both specimens.

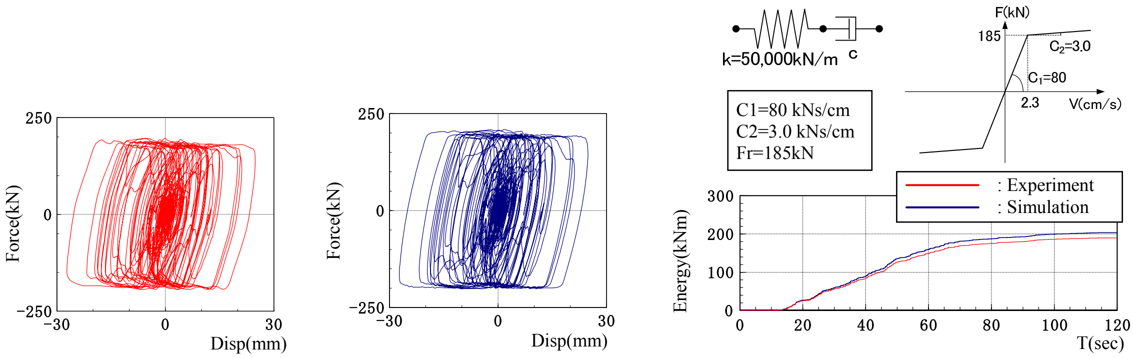


(a)S130 (b)L140

Figure 14. Force-velocity relation of under harmonic excitation

5.3 Result of Simulation Analysis

Fig. 15(a) shows the force-displacement relation of L140 in the diagonal position with random loading. The input wave is the record of seismic analysis against L2 earthquake (Random) in the previous chapter, and the maximum input displacement is about 27mm for the axial direction of the damper during 180 seconds of this record. Based on the results of this experiment, we conducted simulation analysis to verify that we can accurately simulate the behavior of the newly developed oil damper. We used the Maxwell model shown in Fig. 15, and the damper's specifications identified from the results of the experiments. Fig. 15(b) shows the force-displacement relation obtained from the simulation analysis. We can confirm that the damper draws a stable loop for all durations and the simulation results correspond closely with the experimental results. In Fig. 15(c), we compare the amount of energy absorption of the experiment with the simulation. We can also confirm that the simulation results correspond closely with the experimental results.



(a) Experiment (b)Simulation (c)Time history of absorption energy

Figure 15. Force-displacement relation under Random Loading (L140)

6. CONCLUSION

This paper has proposed a new structural control system that realizes substantial earthquake response reduction utilizing torsional vibration. This system consists of an eccentric core structure, flexible perimeter frames with pin-jointed post-columns that support only vertical loads, slab elements that transmit shear force between the core structure and the perimeter frames, and energy dissipation devices (dampers) installed in the perimeter frames. This system is nicknamed "Damper Tube Structure (DTS)".

We first demonstrated the features and advantages of the DTS through earthquake response analyses with the design example of high-rise building. It was confirmed that the DTS realized substantial response reduction effect in spite of a unique and bold structural composition, and reasonable design with good cost performance was possible even against a severe earthquake and a high criteria. In addition, it should be noted that the DTS showed high robustness against various fluctuations of design parameters or input earthquake levels. We have also demonstrated the experimental results of the newly developed oil damper with slender shape and high performance designed to meet the needs of this system. Because this damper works under very small vibration, high habitability is realized in spite of the relatively small structural stiffness. We believe the DTS has not only high potential of response control but also a possibility of realizing a new architectural design in countries like Japan that are subject to severe earthquakes.

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