



## FULL-SCALE E-DEFENSE SHAKE TABLE TESTS ON 5-STORY STEEL BUILDING WITH VARIOUS DAMPERS

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### ABSTRACT

Realistic simulations of earthquake responses were conducted in March 2009 for the full-scale 5-story building specimens with dampers using the E-Defense, the world's largest three-dimensional shake table. The building was tested repeatedly, inserting and replacing each of 4 damper types, i.e., steel damper, oil damper, viscous damper, and viscoelastic damper. This paper discusses test concept, method and test results as well as details of the 5-story building specimen. Performance improvement by the dampers will be addressed for moderately tall buildings that constitute a major portion of the building stock.

### Introduction

The E-Defense shaking table facility, whose construction was completed in early 2005, is the largest earthquake simulator capable of subjecting full-scale structures to the strongest earthquakes recorded in the world. Using the facility, three major research projects were completed on geostructures, wooden buildings, and reinforced concrete buildings, respectively. Currently, projects on steel buildings and bridges are being pursued. Figure 1 shows overall organizations for the steel building project that focuses on moment-resisting frames, innovative methods for new or existing buildings, nonstructural elements, and protective systems. It is pursued by four working groups (WG's) shown in Figure 1. This paper addresses the work of Damper and Isolation Systems WG. This paper discusses test concept, method and test results, as well as details of the 5-story building. The building was tested repeatedly, inserting and re-placing each of 4 damper types, i.e., steel damper, oil damper, viscous damper, and viscoelastic damper. Moderately tall buildings that constitute a major portion of the building stock will be considered.

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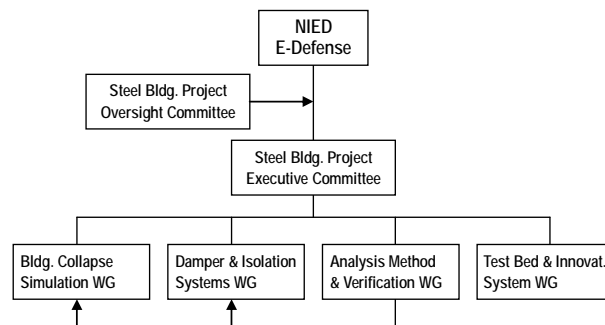


Figure 1. Organization of E-Defense steel project.

## Test Concept and Method

### Validation of Passive Control Technology

Japan has constructed the largest number of passively-controlled buildings, and is believed to have conducted the most extensive research to realize various control schemes. A variety of dampers are being produced by more than twenty manufacturers and more than ten general construction companies in Japan. Numerous technical papers on the schemes are also published. Most major Japanese buildings designed and constructed after the 1995 Kobe earthquake are either base-isolated or passively-controlled in order to better protect the building and its contents. However, because of their short histories, the schemes have never been attested under the major and catastrophic quakes, while they are increasingly used in Japan. Thus, it is extremely important to validate these advanced schemes by realistic experiments, before occurrence of such earthquakes. The full-scale shake table test made possible by the E-Defense would be the best option for such validation.

### Moderately Tall Steel Buildings

A 5-story steel building is considered as the specimen, since it represents many office buildings seen in Japan; it is about the tallest of the majority of steel building stock, and; it tends to deform, if not damped, much more than taller steel buildings under the major quake. The last point is discussed below:

Figure 2 shows spectral displacement  $S_d$  vs. acceleration  $S_a$  for the design basis earthquake (DBE) and maximum considered earthquake (MCE). The spectra for the ground motion recorded at JR Takatori Station during the 1995 Kobe Earthquake are also shown. Damping ratio 5% is considered. The plots are for elastic responses, but they will be used here as crude estimates for inelastic responses.

It is customary in Japan to estimate the building vibration period  $T$  by the building height  $H$ . Possible range of  $T$  for a building with  $H=16\text{m}$ , similar to the specimen height is shown in Figure 2. Story drift angle averaged over the building height  $\theta_{avg}$  is also shown, by approximating it as  $S_d/(2H/3)$ . The  $2H/3$  is the effective height, corresponding to a case of straight mode shape.

It was statistically found that the Japanese code formula  $T=0.03H$  is reasonably accurate

for taller Japanese MRFs. In contrast, for moderately tall MRFs considered here, the range of  $T=0.05H$  to even  $0.07H$  is found to be more appropriate. From Figure 2, this would lead to  $\theta_{avg}=0.017$  to  $0.027$  under the DBE, suggesting significant structural and non-structural damage, as vibration period is longer. Such an MRF would be vulnerable against stronger quakes such as the Takatori motion whose spectra are much larger (Fig. 2). Moreover, consequently large ductility demand will produce  $\theta_{avg}$  larger than estimated by this elastic approach. Further, inelastic drift may be highly non-uniform and concentrate in a particular story, largely exceeding  $\theta_{avg}$ . These were demonstrated by the Building Collapse Simulation WG (Fig. 1), testing a full-scale 4-story steel building ( $H=14.4\text{m}$ ) with  $T=0.063H$  (Suita 2009, Yamada 2009). The building collapsed under the Takatori ground motion, due to the large drift and non-ductile column behavior at the 1st story.

Accordingly, moderately tall steel MRF tends to be vulnerable due to its larger deformation caused by the relatively long vibration period. The Japanese code limits the story drift angle to  $1/200$  under the static force estimated from the acceleration spectrum similar to that of DBE (Fig. 2). However, since acceleration is constant and thus limited in the shorter period range (Fig. 2), the drift limit is easily satisfied by the short and moderately tall buildings. This results in larger flexibility and thus longer vibration of such buildings.

Based on these, and since simply increasing the MRF member sizes to control drift would be very uneconomical, the use of dampers is believed to be an alternative and attractive option. In spite, passive control is hardly utilized for short and moderately tall buildings in Japan, since the code does not yet adequately address such applications. Moderately tall building, therefore, was selected as the specimen, because of its significant potential to impact the above circumstances.

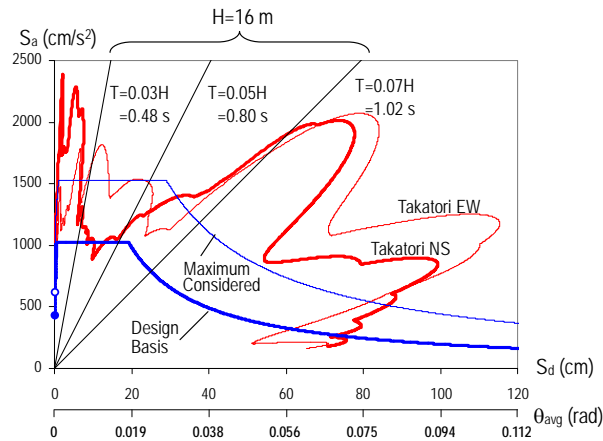


Figure 2. Displacement vs. acceleration spectra (Design basis earthquake, maximum considered earthquake, and JR Takatori ground motions, 5% damping ratio).

## Test Method

The objective of the present test is to validate reliability of the passive control technology by conducting realistic experiments. Four major types of dampers are selected, and for the economical reason the building will be tested repeatedly, inserting and replacing each of the damper types. In this regard, the frame members must be kept almost elastic without much residual deformation. Such requirement is considered to be important for design of actual

damped building, thus, a practical beam column connection detail to enhance the elastic limit of the frame is developed and used for the specimen.

The aforementioned JR Takatori ground motion that caused collapse of the 4-story specimen is used in order to demonstrate contrasting performance and appeal to the community for promoting safer seismic environments. In this regard, the building without dampers will be tested at the end of the test series, which is expected to demonstrate that even the MRF with improved design will suffer significant deformation and damage in contrast to the damped case. The JR Takatori motion will be scaled 0.05, 0.1, 0.2, 0.4, and 1.0 times, in order to compare the performance among the four damped frames as well as un-damped frame at various seismic levels. White noise excitation as well as free vibration test will be pursued. Ambient vibration frequencies and modes are also constantly monitored after erection of steel skeleton, until end of the tests. Dynamic properties at moderate shaking will be also measured by operating two vibrating machines set on the building roof, during the break between the shake table tests.

The number of data channels will be about 1,350 which is the largest among all the tests performed previously at E-Defense. The quantities to be measured are as follows:

- (1) Strains: columns strains, beam strains, damper strains, anchor bolt strains, slab reinforcement strains, slab surface strains, panel zone strains, and cladding support member strains, etc.
- (2) Deformations and Displacements: story drift and twisting deformation, damper deformation, foundation rocking, column rotation, beam rotation, ceiling displacement, stairway displacement, exterior panel in- and out-of-plane displacement, partition in-plane displacement, door shear deformation, and ceiling edge and partition relative displacement, etc.
- (3) 3D-Accelerations: shake table accelerations, each floor accelerations, story drift support accelerations, ceiling accelerations, and cladding accelerations, etc.
- (4) Others: pressure between ceiling edge and partitions, ceiling hanger reaction force, motion records outside and inside the building (including axial and transverse damper deformation) etc.

### **Building Frames with Dampers**

Japanese dampers can be categorized into five major types shown in Figure 3, and four types such as shown in Figure 4 are considered: they are steel, oil, viscous, and viscoelastic dampers. The building will have 12 dampers of the same type with three to four different sizes. For each type, full-scale dampers of three different sizes were dynamically tested at Tokyo Institute of Technology (Kasai 2008). Detailed descriptions for the test results and analytical models are described elsewhere (Ooki 2009).

As shown in Fig. 5, the building is 5-story with two bays in each direction. Due to the reduction in budget, the building is made smaller than originally planned and described elsewhere (Kasai 2007, 2008). The plan dimension is 10m  $\times$  12m, and total height from the upper surface of a stiff foundation beam is 15.8 m (Fig. 5). Seismically active weight of the superstructure is 4,730 kN, including all structural/non-structural components and a portion of live load (Table 1).

The frame members of the superstructure consist of either rolled or built-up wide-flange beam sections of 400 mm deep (Table 2(a)), and cold-formed square box column sections of 350 mm  $\times$  350 mm (Table 2(b)). Note that each span consists of three beam portions, a center beam portion and two end beam portions that are bolt-connected through the splice plates on flanges and webs. For the beams of MRF bays (G2, G3, G12, and G13 in Fig. 5), the center portion uses smaller cross section, as indicated by Table 2(a). And for the beams of damper bays (G1 and

G11), the same sections are used for all the three portions in order to resist large axial forces transmitted from the damper. The coupon tests for all members indicate actual yield stresses of the columns and beams were in average about 1.2 times the nominal values (Table 2(c)).

All the beam and column connections will be a fully-restrained type. For the beams of MRF bays, the flange is haunched to increase yield rotation and to delay onset of yielding. And for the beams of damper bays, haunch was considered unnecessary due to large sections created by the gusset plate (Kasai 2009a).

Figure 6 shows exterior views of the building. The precast light-weight curtain walls and glass curtain walls are provided to the 1st and 2nd story levels only. The walls are not attached to the damper bays for ease of dismantling/mantling the dampers. Figure 7 shows four types of damper inserted in the building specimen.

The steel deck with normal concrete on top will be considered and fully composite beams will be created. The concrete thickness is 80 mm above the corrugated metal deck of 75 mm high. The stairway (Fig. 5) is detailed to slide during shaking, thus, it does not produce significant twisting against building. At every story level above the 1st, partitions with doors are constructed. Two types of ceilings with sprinkler systems, as well as mechanical equipment are placed at some story levels.

Viscous	Oil	Viscoelastic	Steel	Friction
Shear/Flow Resist. Panel, Box, Cylinder	Flow Resist. Cylinder	Shear Resist. Brace, Panel, etc.	Axial/Shear Yielding Brace, Panel, etc.	Slip Resist. Brace, Panel
$F = C \cdot \dot{u}^n$	$F = C_1 \cdot \dot{u} \text{ or } C_2 \cdot \dot{u}$	$F = K(\omega) \cdot u + C(\omega) \cdot \dot{u}$	$F = K \cdot f(u)$	$F = K \cdot f(u)$

Figure 3. Five major types of dampers used in Japan.

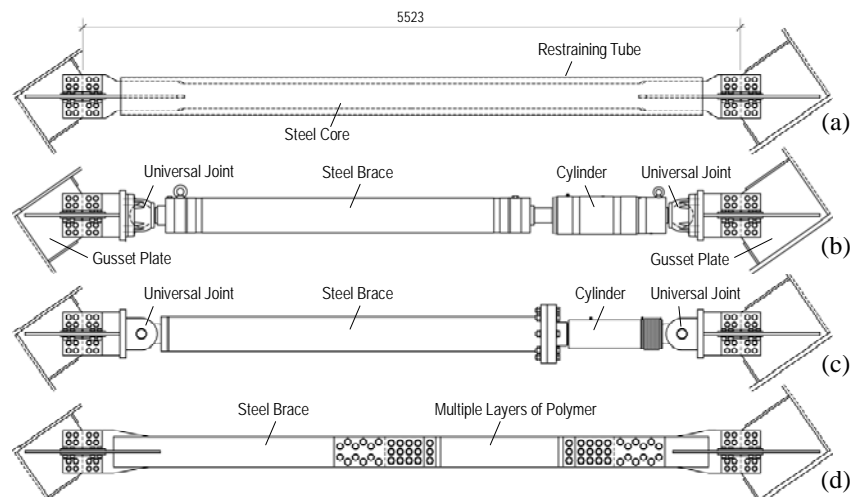


Figure 4. Sizes and configurations of 4 types of dampers to be used (between 2nd and 3rd floors): (a) steel, (b) oil, (c) viscous, and (d) viscoelastic dampers.

Table 1. Breakdown of seismically active weight for the full-scale 5-story building specimen (Unit: kN).

Floor	Floor	Steel frame	Exterior wall	Interior wall	Live load	Others	Total weight
RF	963.4	111.6	127.8	20.3	81.7	150.0	1454.8
5F	436.2	99.5	100.3	26.5	98.8	37.5	798.8
4F	436.2	117.4	100.3	26.5	98.8	37.5	816.7
3F	436.2	122.7	100.3	26.5	98.8	37.5	822.0
2F	436.2	131.3	108.8	28.7	98.8	37.5	841.3
Total	2708.2	582.5	537.5	128.5	476.9	300.0	4733.6

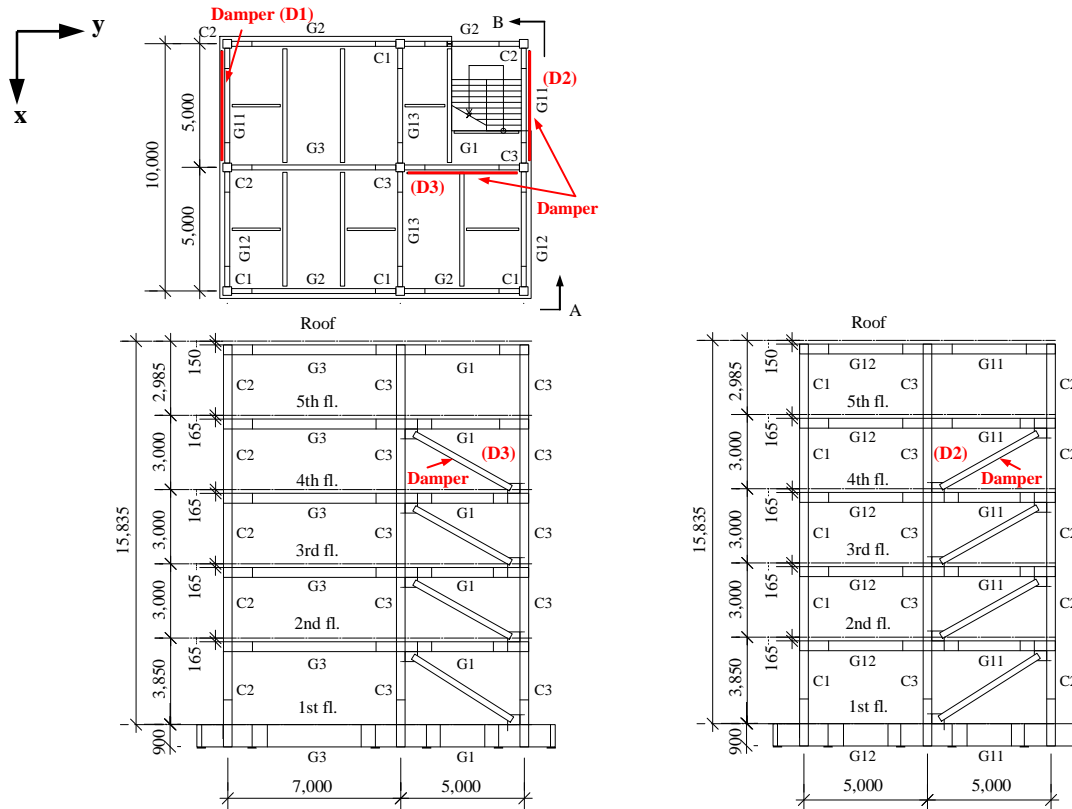


Figure 5. Plan and elevations for full-scale 5-story building specimen.

Table 2. List of cross section sizes for (a) all girders, (b) all columns, and (c) Yield and ultimate strengths of steel used (actual vs. nominal values).

Floor	(a)					(b)			
	G1(Full portion)	G2(End portion)	G2(Center portion)	G3(End portion)	G3(Center portion)	Story	C1	C2	C3
RF	H-400x200x9x12	BH-400x200x9x12	H-400x200x9x12	BH-400x200x12x16	H-400x200x9x12	5	□-350x350x12x12	□-350x350x12x12	□-350x350x12x12
5F	BH-400x200x12x16	BH-400x200x12x16	H-400x200x9x12	BH-400x200x12x16	H-400x200x9x12	4	□-350x350x12x12	□-350x350x12x12	□-350x350x12x12
4F	BH-400x200x12x19	BH-400x200x12x19	H-400x200x9x16	BH-400x200x12x19	H-400x200x9x16	3	□-350x350x16x16	□-350x350x16x16	□-350x350x19x19
4F	H-400x200x12x22	BH-400x200x12x19	H-400x200x9x16	BH-400x200x12x19	H-400x200x9x16	2	□-350x350x16x16	□-350x350x19x19	□-350x350x19x19
2F	H-400x200x12x22	BH-400x200x12x19	H-400x200x9x16	BH-400x200x12x19	H-400x200x9x16	1	□-350x350x19x19	□-350x350x22x22	□-350x350x22x22
1F	BH-900x500x16x28	BH-900x500x16x28		BH-900x500x16x28					

Floor	(a)					(c)	
	G11(Full portion)	G12(End portion)	G12(Center portion)	G13(End portion)	G13(Center portion)	$\sigma_y$ (N/mm <sup>2</sup> )	$\sigma_u$ (N/mm <sup>2</sup> )
RF	H-400x200x9x12	BH-400x200x9x12	H-400x200x9x12	BH-400x200x9x12	H-400x200x9x12	346-398	430-470
5F	BH-400x200x12x16	BH-400x200x12x16	H-400x200x9x12	BH-400x200x12x16	H-400x200x9x12	295	400
4F	BH-400x200x12x16	BH-400x200x12x19	H-400x200x9x16	BH-400x200x12x19	H-400x200x9x16	331-422	510-557
4F	BH-400x200x12x19	BH-400x200x12x19	H-400x200x9x16	BH-400x200x12x19	H-400x200x9x16	325	490
2F	H-400x200x12x22	BH-400x200x12x19	H-400x200x9x16	BH-400x200x12x19	H-400x200x9x16	342-365	510-520
1F	BH-900x500x16x28	BH-900x500x16x28		BH-900x500x16x28		325	490



Figure 6. Exterior views of the building specimen under construction (Dec. 2008 and Jan. 2009)



Figure 7. Four types of damper inserted in the building specimen (Steel, viscous, oil, and viscoelastic dampers, respectively)

### Test Results

Measured responses of main structural components such as dampers, frame and system during the shake table test are as follows.

Figure 8 shows comparison between the story shear based on inertia forces and the story shear based on member forces at 1st, 3rd, and 5th story in x-direction for the building with steel dampers under the 100% Takatori motion. As Fig. 8 shows, both story shear based on inertia forces and story shear based on member forces match well. In addition, the former is about 10% larger than the latter probably because of the contribution from non-structural components.

Figure 9 shows relationship between damper forces and damper stroke of each of the four types of dampers at 1st story under the 15%, 50% and, 100% Takatori motions. As shown in Fig. 9(a), steel dampers behave elastically under 15% Takatori motion, and elasto-plastically under 50% and 100% Takatori motions. As Fig. 9(c) shows, oil dampers behave linearly under 15% and 50% Takatori motions, and non-linearly under 100% Takatori motion due to working of relief valve. As shown in Fig. 9(d), viscoelastic dampers behave linearly regardless of shaking intensity. Figure 10 shows relationship between story shear based on inertia force and story drift for the building with steel dampers. As Fig. 10 shows, hysteresis curves at 1st and 3rd stories with dampers indicate significant energy dissipation by the steel damper. On the other hand, hysteresis curve at 5th story without damper indicates elastic behavior. Figure 11 shows peak responses such as story shear, story drift angle and floor acceleration of building specimen with four types of dampers under 50% and 100% Takatori motion. In addition, peak responses of building specimen without damper are shown in Fig. 11 for comparison. Note that, for the 100% Takatori motion, they are extrapolated as 2 times those for 50% Takatori, because shaking was

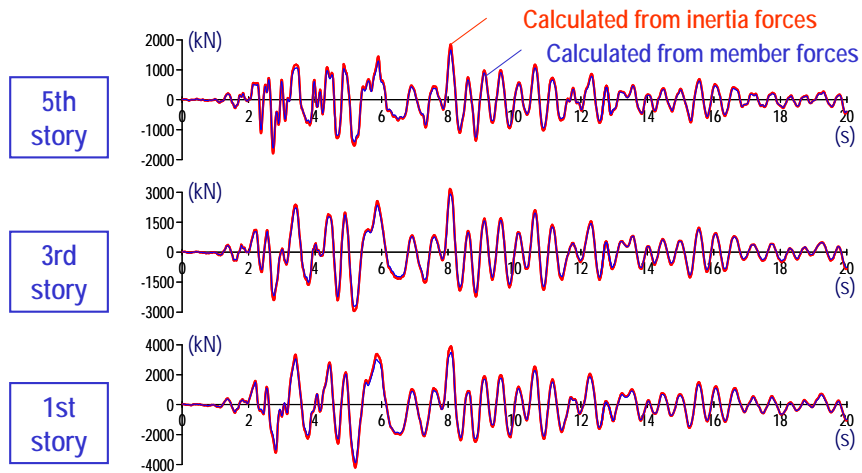


Figure 8. Comparison between story shear based on inertia forces and story shear member forces (with Steel dampers, 100% Takatori, X-Dir.)

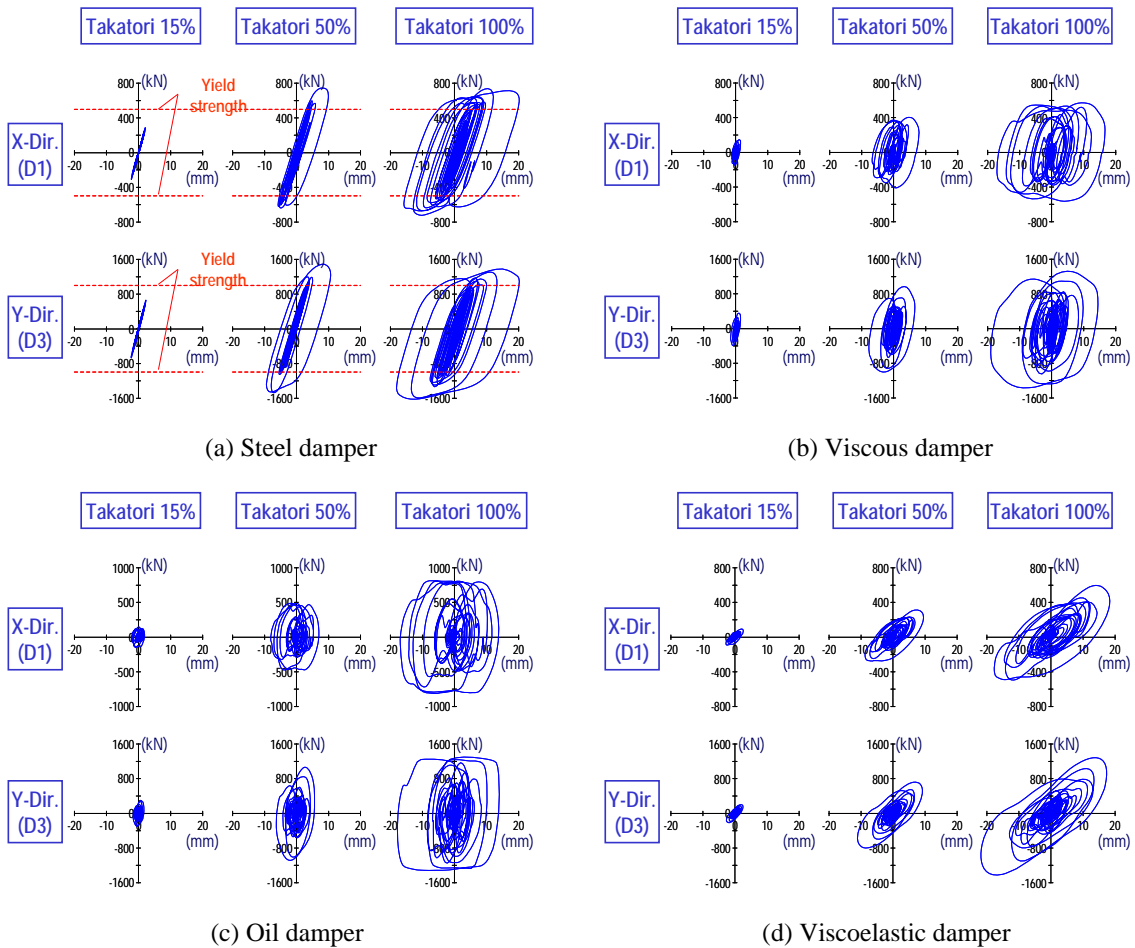


Figure 9. Relationship between axial damper forces and damper stroke of four types of dampers (1st story)



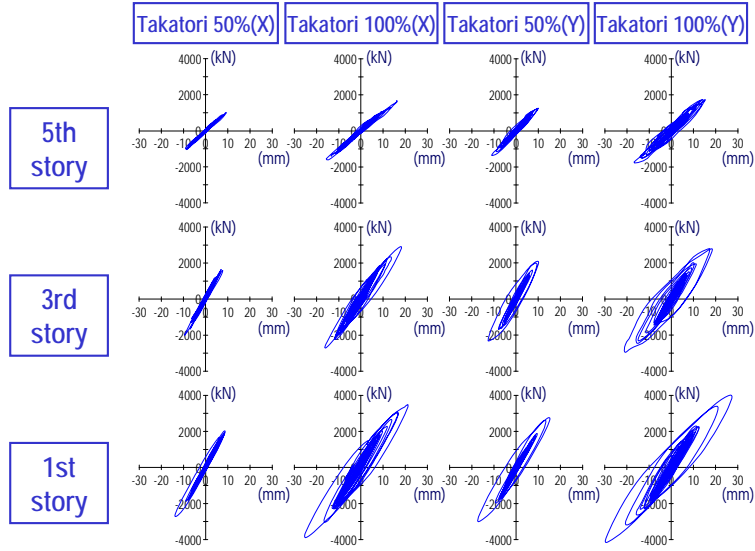


Figure 10. Relationship between story shear based on inertia force and story drift (with steel dampers)

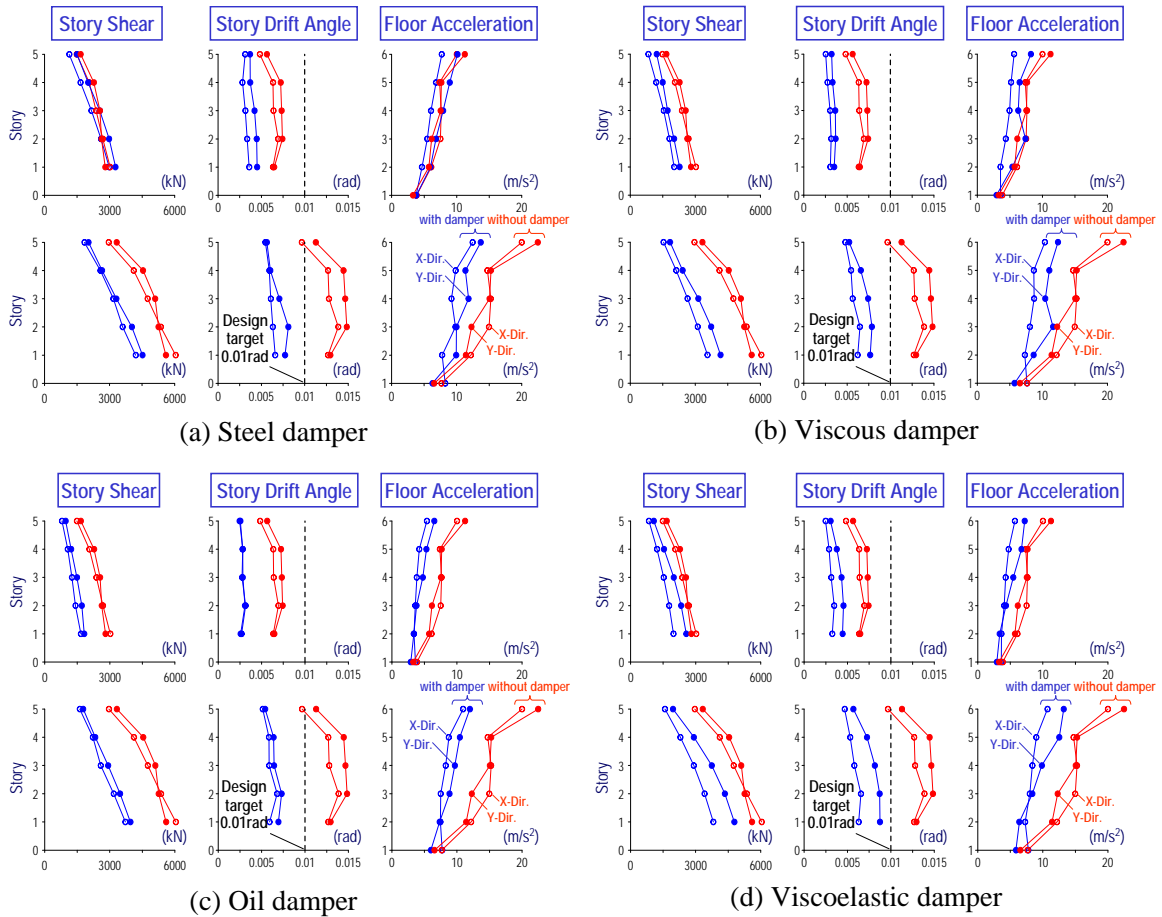


Figure 11. Relationship between story shear based on inertia force and story drift (with steel dampers)

limited up to the level of 70% Takatori motion for the safety reason. As shown in Fig. 11, story drift angle under 100% Takatori motion for the building with each type of damper is less than the design target value of 1% radian. As a whole, peak responses of the building having dampers are considerably less than those without dampers.

### Summaries and Conclusions

Realistic three-dimensional shaking table tests were conducted for full-scale 5-story building specimens with (March 2009) or without (April 2009) dampers. This paper has described the test concept, method and results, as well as details of the 5-story building specimen.

### Acknowledgments

This study is a part of “NEES/E-Defense collaborative research program on steel structures,” and was pursued by the Damper and Isolation WG. The Japan team leader for the overall program and the leader for the WG is Kazuhiko Kasai, Tokyo Institute of Technology. The WG members not listed as the authors also contributed to the present effort, and their contributions are greatly appreciated. The authors also acknowledge the financial support provided by the National Research Institute for Earth Science and Disaster Prevention (NIED).

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