VALUE-ADDED 5-STORY STEEL FRAME AND ITS COMPONENTS: PART 1 – FULL-SCALE DAMPER TESTS AND ANALYSES

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ABSTRACT :
Realistic three-dimensional shaking table tests will be conducted in February and March 2009 for full-scale 5-story building specimens with dampers. The building will be tested repeatedly, inserting and replacing each of 4 damper types, i.e., steel damper, oil damper, viscous damper, and viscoelastic damper. The shaking table test uses 16 dampers for each damper type. Extensive preliminary analyses and experiments have been conducted. For each damper type, 3 different capacities ranging approximately from 400 kN to 1,800 kN were tested, and correlated with analyses using the numerical models being recognized as the most accurate and practical among those available. The 5-story building with each damper type was also analyzed statically and dynamically. According to the results, the deformation of the building will be kept small even against the strong ground motion recorded during the 1995 Kobe earthquake. This paper explains such preliminary investigations as well as the blind analysis contest to be held regarding the performance of the 5-story building.

KEYWORDS:
E-Defense, Shaking Table, Passive Control, Value-Added Building, Steel Frame, Dampers, Full-Scale Tests

1. INTRODUCTION

The Japanese social desire for adopting passive control schemes has increased considerably after the 1995 Kobe earthquake. The schemes are now typically used for major buildings, and are modified and used even for many small residential buildings, in order to better protect the building and its contents. However, because the history of passive control is short, the technology has never been attested under the major and catastrophic earthquakes, while it is increasingly used in Japan. Therefore, it is extremely important to validate reliability of this technology by realistic simulations, before such earthquakes occur.

Pursuant to this, a full-scale building with dampers will be examined in February 2009 using the E-Defense, the world's largest three-dimensional shaking table. The experiment is a part of the 5-year E-Defense steel building project addressing moment-resisting frames, innovative methods for new/existing buildings, protective systems, and nonstructural elements (Kasai et al., 2007). The present paper reports a part of the preliminary study such as full-scale tests and analyses of individual dampers, and three-dimensional analyses of the 5-story building. It also briefly explains the blind analysis contest to be held regarding performance of this building,

2. FULL-SCALE 5-STORY BUILDING SPECIMEN

2.1. Value-Added Building Specimen

As shown in Fig. 1, 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 et al. 2007, 2008). In spite, the test is still by far the largest and the most realistic, among those conducted for passively-controlled buildings. The plan dimension is 10m × 12m, and total height from the upper surface of a stiff foundation beam is 15.8 m. Seismically active weight of the superstructure is 4,730 kN, including all structural and non-structural components as well as a portion of live load.

The frame members of the superstructure consist of wide-flange beam sections of 400 mm deep, and square box column sections of 350 mm × 350 mm. The expected steel yield strength for the beam and column are 358 MPa and 325 MPa, respectively. All the beam and column connections will be a fully-restrained type. The steel deck with concrete on top will be considered and fully composite beams will be created. Note that the beam flange is haunched to increase yield rotation and to delay onset of yielding (Kasai et al. 2007). Some stories of the building will be provided with glass curtain wall, pre-cast light-weight curtain wall, partitions with doors, several types of ceilings with sprinkler systems, and mechanical equipment. The study on the behavior of non-structural components is a part of the major US-Japan collaborative research program. The building will have 12 dampers (Fig. 1) of the same type with three to four different sizes. Four major damper types are considered: they are steel, oil, viscous, and viscoelastic dampers (Section 3).

The specimen is designed to be the "value-added" building whose structural and non-structural components are protected from a major seismic attack. The story drift angle is required not to exceed 0.005 (=1/200) rad. under the so-called level 2 (design basis) earthquake, which is much more stringent than 0.01 (=1/100) rad. usually considered for a conventional building. At the drift angles limited to 0.01 rad., the frame would be almost elastic with no damage. These points will be confirmed in Sec. 2.2 and Sec. 4, by a series of analyses.

2.2. Static and Eigenvalue Analyses

Using the seismically active story weight (Table 1a), the so-called A_i-distributions (BCJ 1991) and the lateral design load distributions (Table 1b) are obtained. The latter is used for static push-over analyses of a three-dimensional building model that includes beam-column elements with axial force and bi-axial moment interaction. Table 1c indicates the story stiffness and fundamental vibration periods of the building in x- and y-directions (Fig. 1), which are obtained from the model without and with elastic steel damper elements, respectively. In contrast to the steel damper, other three types of dampers are velocity-dependant, and they are therefore examined via dynamic analysis (see Section 4). Fig, 2 shows the results from the static push-over

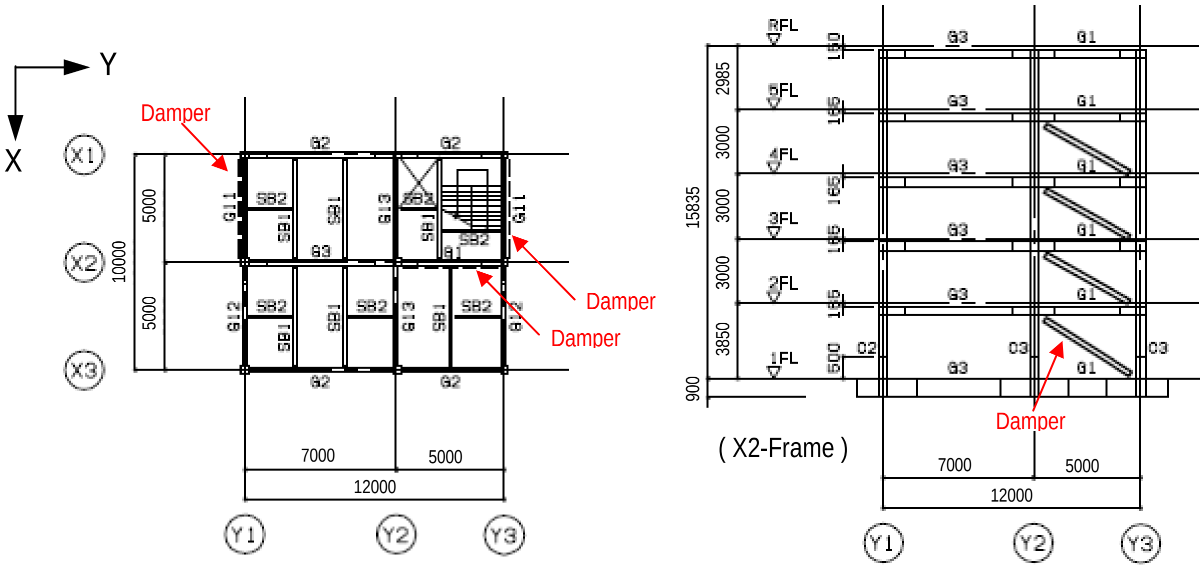


Fig. 1 Full-Scale 5-story Building with Dampers (E-Defense Tests)

Table 1 Data of 5-Story Specimen: (a) Story Weight, (b) Lateral Force, and (c) Story Stiffness (kN/cm) and Vibration Period

(a)

Story Level	Weight (kN)
5	1455
4	799
3	817
2	822
1	841
Total	4734

(b)

Story Level	Lateral Force	Shear Force
5	0.52	0.52
4	0.17	0.69
3	0.14	0.83
2	0.10	0.93
1	0.07	1.00

(c)

Story Level	Frame		Frame with Steel Damper	
	X	Y	X	Y
5	776	703	945	848
4	805	712	1472	1264
3	929	820	1839	1606
2	1004	878	2256	1992
1	1055	943	2254	2309
Natural Period	0.74 s	0.79 s	0.53 s	0.56 s

analyses applying the lateral load in either x- or y-direction, and Fig. 3 shows those applying the lateral load in both x- and y-directions simultaneously. From now on these cases will be named as “x-loading case”, “y-loading case”, and “simultaneous loading case”. The solid and dashed lines indicate the results without dampers and with dampers, respectively.

Without Dampers: The story stiffness and vibration period of the frame in x-direction are about 12% larger and 6% smaller than those in y-direction, as indicated by Table 1c. The vibration periods in x- and y-directions are 0.047 and 0.050 times the building height of 15.8 m, much longer than that (0.03 times) given by the code and considered typical for taller steel moment resisting frames in Japan. In either x- or y-loading case (Fig. 2), the frame shows no plastic hinge until the story drift angle exceeds 0.01 rad. In simultaneous loading case (Fig. 3), the plastic hinge forms at the column base when story drift angle reaches 0.008 rad. However, it is found that the hinge does not form in either the beam or column, until the drift angle exceeds 0.01

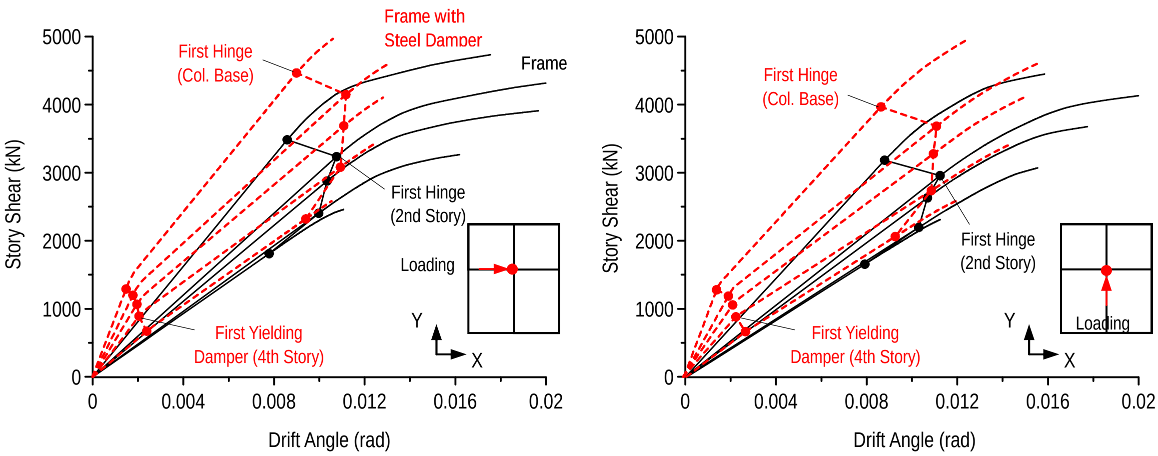


Fig. 2 X-Loading Case and Y-Loading Case (Solid Line: Frame, Broken Line: Frame with Steel Dmaper)

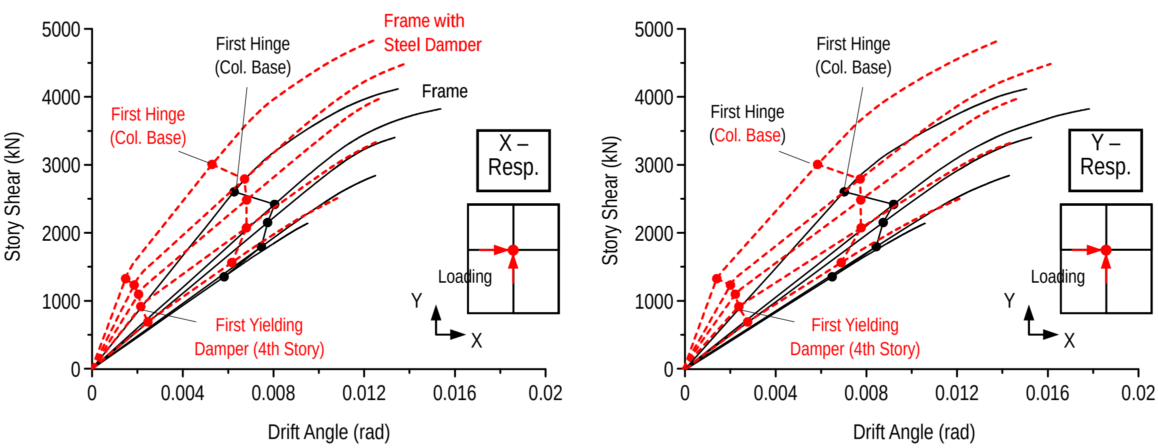


Fig. 3 Simultaneous Loading Case: Reponses in X-Direction and Y-Direction, Respectively

rad. Note also that the beam haunch detail explained earlier has increased the elastic limit story drift by about 20% , although not shown.

With Steel Dampers: By adding the dampers, the story stiffness and vibration period of the building shifts to 2 and 0.7 times, respectively, as indicated by Table 1c. The steel dampers are designed to yield at the story drift angle of about 0.002 rad., and energy dissipation occurs well before reaching the target story drift angle of 0.005 rad. (design basis earthquake) and 0.01 rad. (catastrophic earthquake) mentioned in Sec. 2.1. In either x- or y-loading case, the frame shows the first plastic hinge at the column base due to increased column axial force caused by the dampers, but this occurs only after the story drift angle reaches 0.01 rad. In simultaneous loading case (Fig. 3), the plastic hinge forms at the column base when story drift angle reaches 0.0065 rad., earlier than the case without damper. However, it is found that the hinge does not form in either the beam or column, until the story drift angle exceeds 0.01 rad. The possibility of weak story mechanism is also checked for larger drift angles: the increased axial load in the column increases number of column plastic hinges, but has not caused such story mechanism. See for instance Fig. 4, for the story drift angle of 1/75 (0.0133) rad.

3. FULL-SCALE DAMPER TESTS AND ANALYTICAL SIMULATIONS

3.1. FourTypes of Dampers

In order to assure performance of the damper to be used in the building as well as to validate analytical model, four types of full-scale dampers (Fig. 5) were dynamically tested at Tokyo Institute of Technology (Kasai et al. 2008). Brief descriptions for each type follow: *Steel damper* utilizes yielding of steel material for energy dissipation. It shows a round curve bounded by bi-linear lines, and can be analytically modeled by using readily available constitutive rules for steel materials. *Oil damper* utilizes flow resistance of the oil with low viscosity. The damper typically has a relief mechanism to switch viscous coefficient to a small value when subjected to a large velocity, making the hysteresis to switch from an elliptical shape to a rectangle shape. *Viscous damper* utilizes flow resistance of the polymer liquid. Its force is proportional to the fractional power of velocity, leading to the hysteresis loop of combined ellipse and rectangle. *Viscoelastic damper* utilizes molecular motion of a polymer for energy dissipation. Hysteresis loop is an inclined ellipse, and the inclination angle and the fatness of the loop depend on the excitation frequency and the temperature.

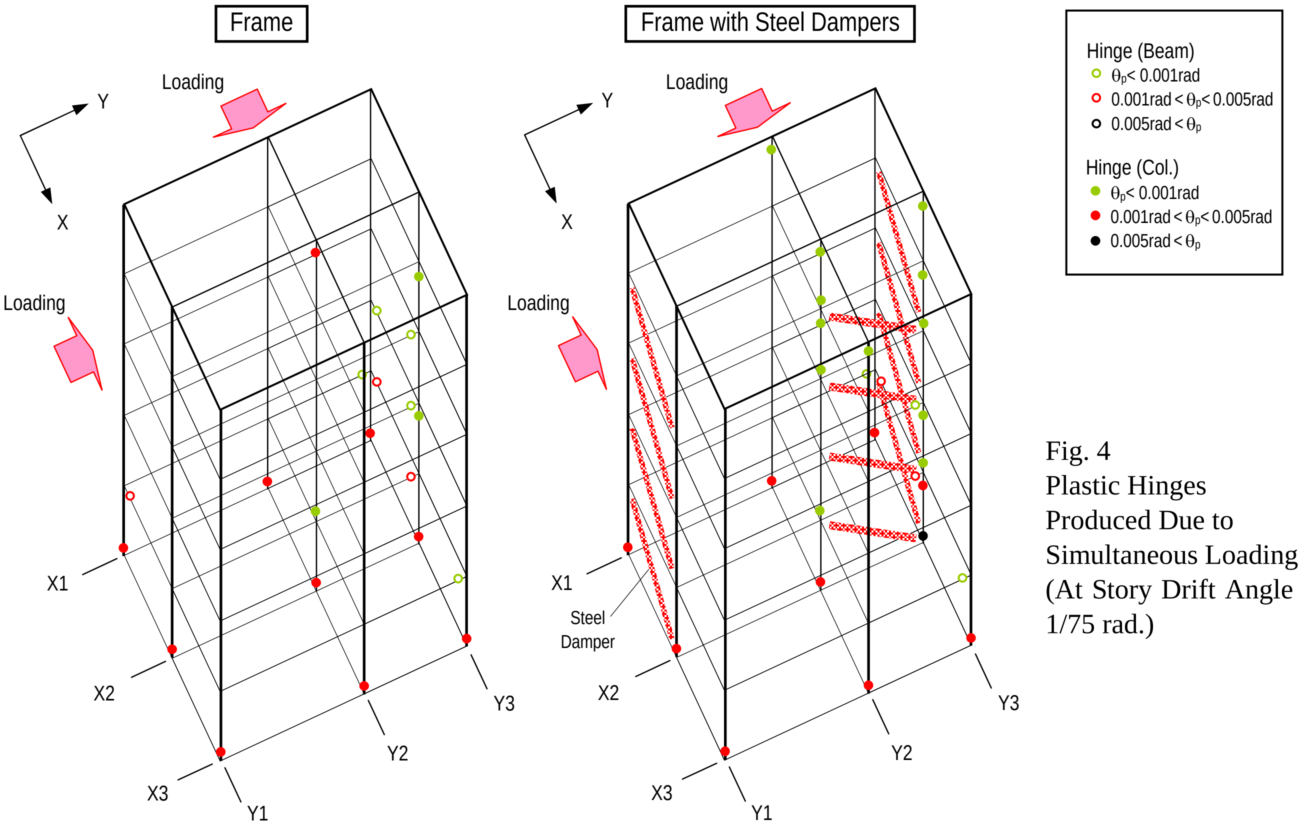


Fig. 4
Plastic Hinges Produced Due to Simultaneous Loading (At Story Drift Angle of 1/75 rad.)

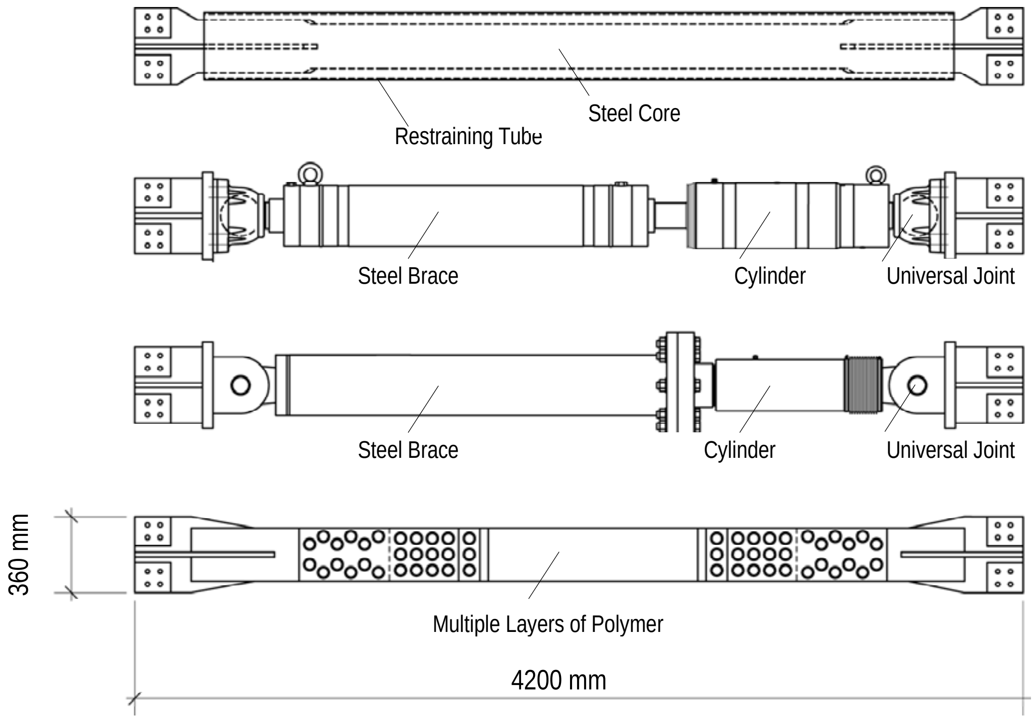
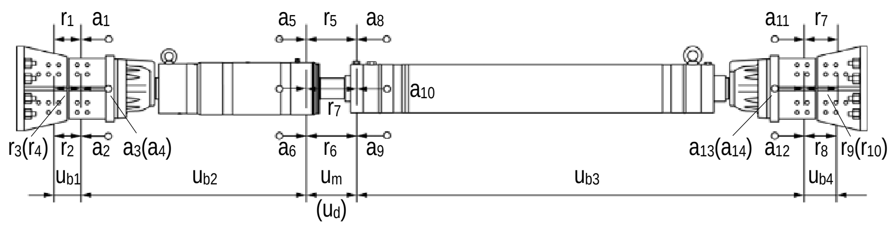


Fig. 5 Steel, Oil, Viscous, and Viscoelastic Dampers Tested (Three Sizes per Type)

3.2. Tests and Analytical Simulations

Dampers of three different sizes per each type were tested, where Fig. 5 shows the largest specimen of each type. As shown in Fig. 6, deformations of various components of the damper-brace assembly are measured, for precise modeling. First, sinusoidal deformation tests are performed, by combining four different peak displacements (0.5, 12, 24, 36 mm) and four frequencies (0.2, 0.5, 1, 2 Hz), except for the loading of combination of 36 mm and 2 Hz that exceeds the performance limit of most dampers. Second, random deformation tests are performed, by using the 1st story drift history obtained from each analysis of 5, 12, and 24-story building models subjected to JMA Kobe NS record and Taft EW record, respectively. Various additional tests are performed on a damper-by-damper basis. For instance, prior to the dynamic tests, steel dampers are statically tested, by applying cyclic deformations of gradually increased peak magnitude.

Fig. 7 shows the hysteretic curves obtained from tests and analytical simulations (Kasai et al. 2004a, b, and c, Yamazaki et al. 2006), in which the analytical models appear to be reasonably accurate. For steel damper, the model is accurate for the static loading case (Fig. 7a left), but must be improved for the dynamic case (Fig. 7a right). Also, although not shown, the responses of oil damper and viscous damper at small deformations deviate from prediction, which must be considered when designing against wind and traffic vibration. The viscous damper has been typically modeled as a series combination of an elastic spring and a nonlinear dashpot whose force is proportional to fractional power of velocity. The stiffness of the elastic spring is found to be limited,



$$u_{b1} = (r_1+r_2+r_3+r_4)/4 \qquad u_{b4} = (r_7+r_8+r_9+r_{10})/4$$
$$u_{b2} = (a_1+a_2+a_3+a_4)/4+(a_5+a_6+a_7)/3 \qquad u_m\,(u_d) = (r_5+r_6+r_7)/3$$
$$u_{b3} = (a_8+a_9+a_{10})/3+(a_{11}+a_{12}+a_{13}+a_{14})/4$$

Fig. 6 Example for Deformation Measurement (Oil Damper Case) thus, current practice of assuming it infinity for the viscous damper is not always appropriate. Analytical model for the viscoelastic damper appears to be accurate from extremely small to large deformations (Figure 6d). Unlike other dampers, increase of force at the first half cycle is remarkable.

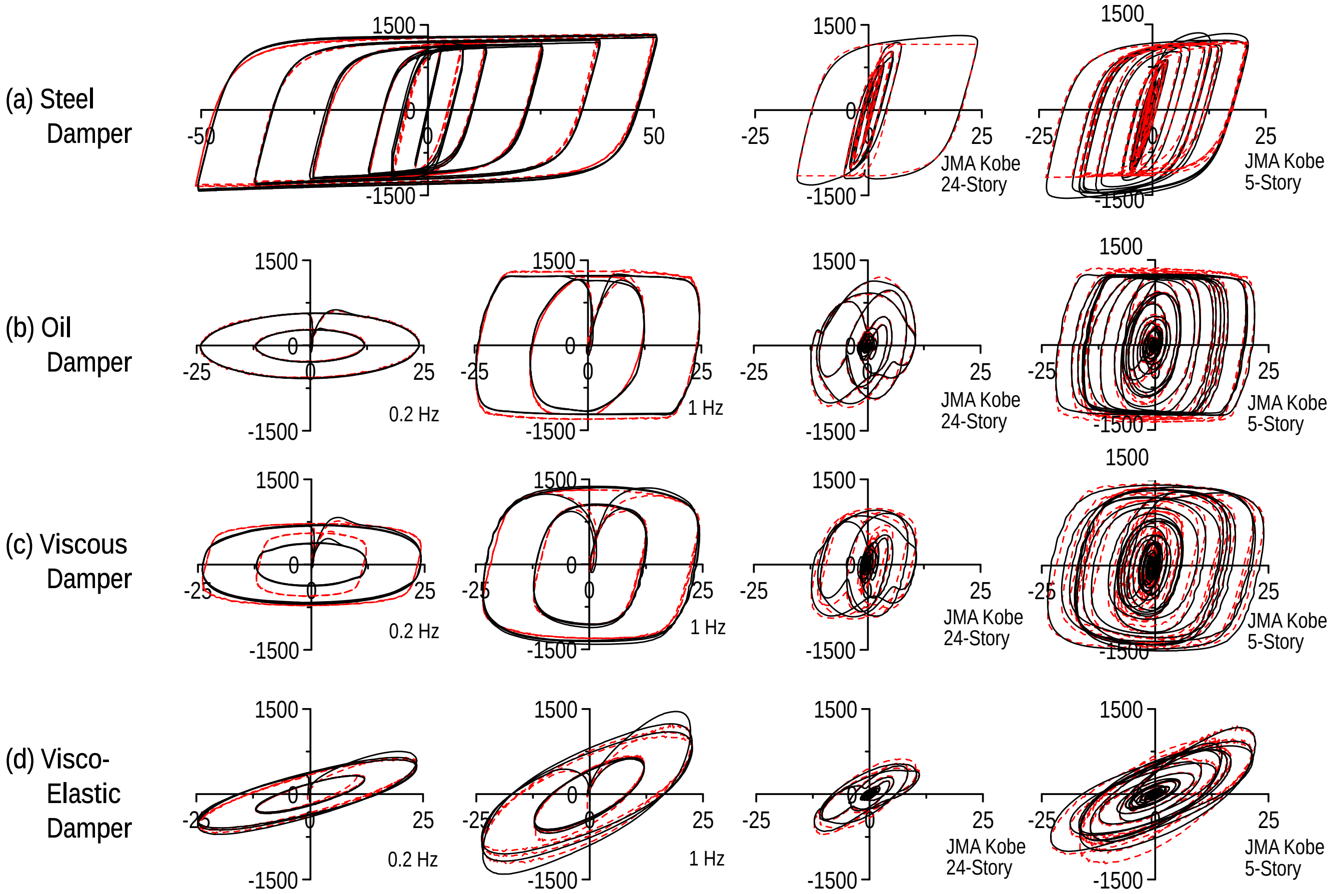


Fig. 7 Results of Full-Scale Damper Tests and Analytical Simulations

4. DYNAMIC ANALYSES OF 5-STORY BUILDING

Fig. 8a shows acceleration spectra S_a of the JR Takatori Station records during the 1995 Kobe Earthquake. The peak ground velocities from both N000E and N090E records are equally 125 cm/s, the largest among the records during the 1995 event, and they are 2.5 times the velocity considered for the design basis (Level-2) earthquake. The records were used for the steel building seismic collapse test in 2007 (Yamada et al. 2008, Suita et al. 2008), and would also be used for the present test. In order to achieve almost equal story drifts in both x- and y-directions, the N000E record may be applied in the direction 45^{o} counter-colckwise from y-axis defined earlier in Figs. 1 to 4. Corresponding S_a in x- and y-directions are shown in Fig. 8b. For the expected effective period of 0.6 to 0.7 sec., the average S_a is 1,500 cm/s^2 or more, when damping ratio is 0.02.

Figs. 9a and 9b show trajectories of the building roof in xy-plane and maximum absolute story drft angle, respectively. The buiding without dampers has displaced primarily in x-direction, and the largest story drift angle is 0.03 rad., which can cause significant damage in both structural and non-structural elements. In contrast, the story drift angle of the buildings with any damper type is limited to 0.01 rad. protecting structural and most non-structural components. Furthermore, the story shear forces and accelerations are controlled to about 0.7 times, although not shown.

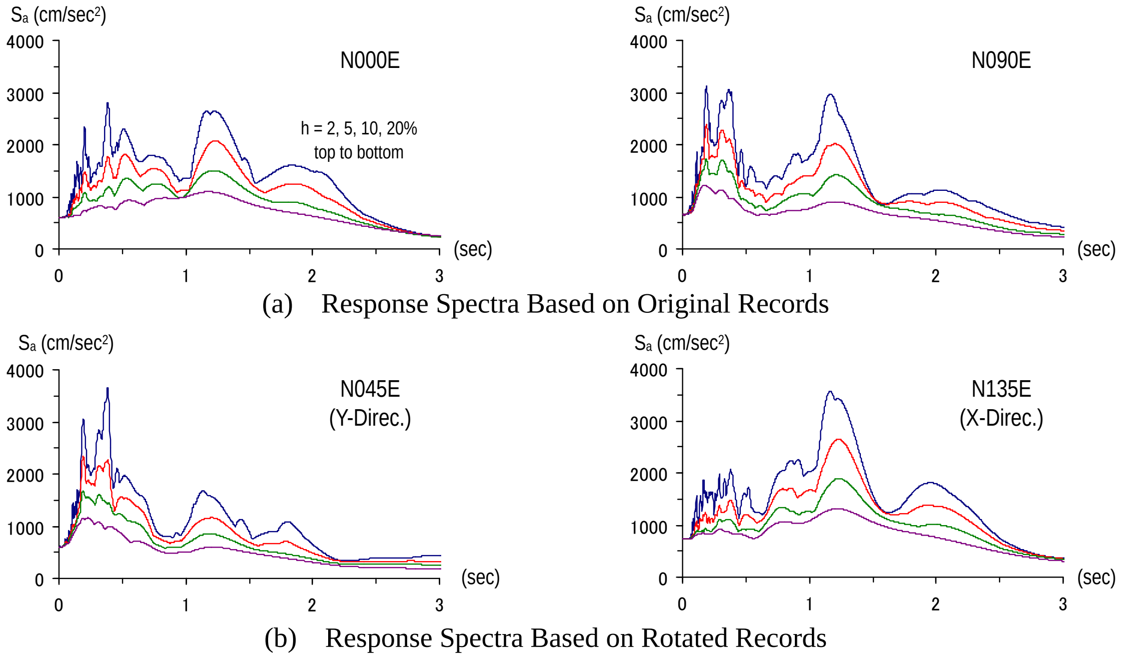
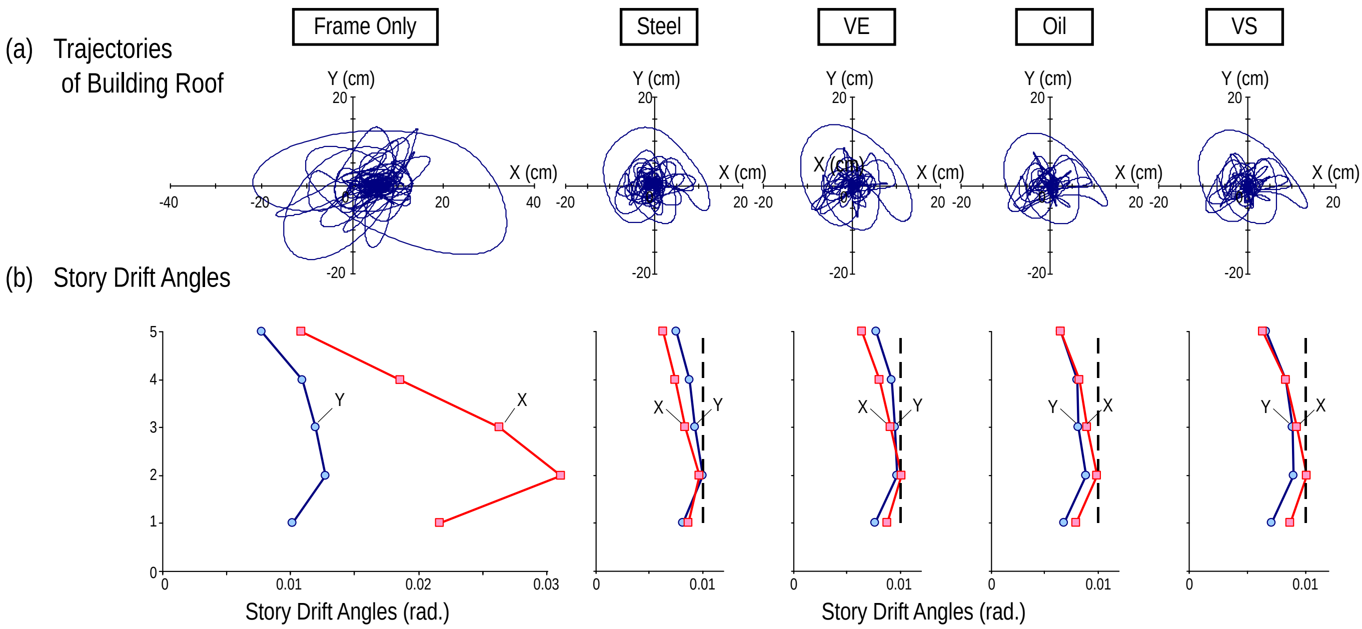


Fig. 8 Acceleration Spectra S_a of the JR Takatori Station Records (1995 Kobe Earthquake).

Fig. 10 also shows the relationship of the damper force and axial displacement (relative displacement between the diametrically opposite nodes where the beam and column centerlines intersect). Due to the energy dissipated and stiffness added (Fig. 10) by the dampers, the excellent performance of the value-added building isobtained, which hopefully will be validated by the full-scale experiments in early 2009. In addition to the above, design basis and smaller earthquakes will also be considered, and the results will be applicable to design of buildings with a variety of levels of the value-added performance.



Figs. 9 Frame without Dampers vs. Frame with Dampers: (a) Trajectories of Building Roof on XY-Plane, and (b) Absolute Peak Drift Angles

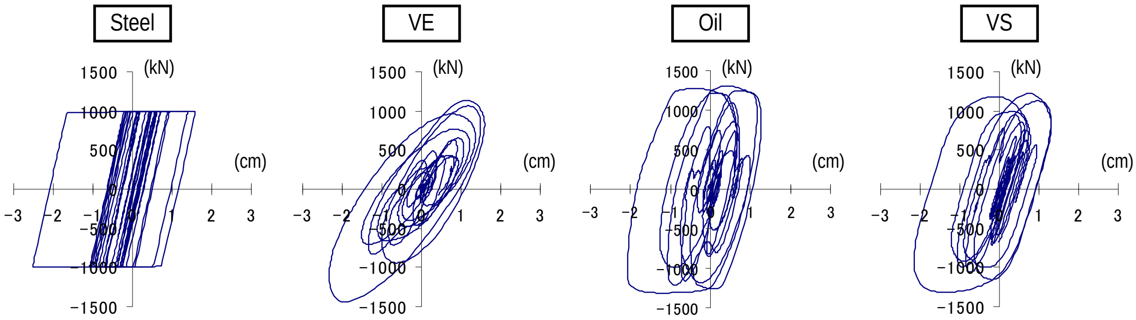


Fig. 10 Damper Force vs. Axial Deformation of Added Component (Deformation of Damper, Brace, and Gusset Connections Combined in Series)

5. SUMMARIES AND CONCLUSIONS

Realistic three-dimensional shaking table tests will be conducted in February and March 2009 for full-scale 5-story building specimens with or without dampers. This paper has discussed the building specimen, preliminary tests and analyses of the full-scale dampers, and preliminary analyses of the building.

Note also that a blind analysis contest, like the one in 2007 for steel building collapse (Ohsaki et al. 2008a, b, and c), will be held as the world-wide competition for the accuracy of analytical prediction prior to the full-scale experiment (see for instance http://www.blind-analysis.jp/index_e.html). It will be announced in fall, 2008.

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