CURRENT STATUS OF BUILDING PASSIVE CONTROL IN JAPAN

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ABSTRACT : The present paper describes three key issues as follows:

(1) A major research program on passive control of buildings: Shaking table tests using E-Defense will be conducted in February 2009, for a full-scale 5-story steel building with or without dampers.
(2) Code and specifications: Japanese code requires nonlinear time history analysis for buildings with dampers, or energy-based analysis when using steel dampers. Unlike the code rules leading to iterative design, JSSI specifications give a direct design method (DDM) for any target performance set by designers or clients.
(3) Damage-Free Design: Under the government support, a large team of researchers/designers has developed a damage-free design method using dampers and frames of the so-called “super high strength steel”. The method is an extended version of the DDM, and its inclusion in the future code is being investigated.

KEYWORDS: Passive Control, JSSI Passive Control Manual, Building Standard Law, Shear Beam Model, Damage-Free Structure Design, Super High Strength Steel

1. INTRODUCTION

Since the 1995 Kobe earthquake, the Japanese social desire for adopting passive control schemes has increased considerably. The schemes are typically used for major buildings, and even for many small residential buildings, in order to better protect the building and its contents. In these schemes, the damper connected to the structural frame dissipates the seismic input energy, thereby reducing the kinetic energy and vibration of the building. 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 passive control are also presented in various Japanese symposiums.

With the above background, Japan has produced the largest number of passively-controlled buildings, and is believed to have conducted the most extensive research to realize various control schemes. This paper explains the present and future of this Japanese technology, especially by referring to major activities related to research and design. It addresses the three key issues such as; extraordinary experimental project to validate passive control performance using different types of dampers, the state of the current code and specifications regarding passive control, and a new direction to promote the so-called damage-free design method even against the catastrophic earthquake. These three issues are discussed in the following sections.

2. VALIDATION OF PASSIVE CONTROL TECHNOLOGY

2.1. Ful-Scale Tests of 5-Story Building with Dampers

The first issue is validation of the passive control technology. 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 this technology by realistic experiments, before occurrence of such earthquakes. Pursuant to this, a full-scale building with dampers will be examined in February and March 2009 using the E-Defense, the world's largest three-dimensional shaking table.

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. 2007a, 2008a, 2008c). 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 center line of the foundation beam is 16.3 m. Seismically active weight of the superstructure is 4,700 kN, including all structural/non-structural components and 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 shall be 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. 2007a). 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 5-story building will have 12 dampers (Fig. 1) of the same type with three to four different sizes. The test will be repeated for different types. Four major damper types are considered: they are steel, viscoelastic, viscous, and oil dampers, and their characteristics will be explained in Section 3. In order to assure performance of the damper to be used in the building as well as to validate analytical model, dampers of three different sizes per each type (Fig. 2) were dynamically tested at Tokyo Institute of Technology (Kasai et al. 2008a, 2008c). The damper capacities were in the range between 500kN and 1500kN, and sinusoidal and random deformation tests were performed. Deformations of various components of the damper-brace assembly were measured, and are used to estimate properties of the analysis models.

2.2. Target Performance of Building Specimen

The specimen is designed to be the "high 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. Furthermore, under the catastrophic earthquake of ground velocity 2.5 times larger, drift angles would be about 0.01 rad. and the frame would remain almost elastic with no damage. The high performance has been predicted by extensive time history analyses, considering the four different types of dampers. The full-scale experiments mentioned above will provide extremely important data to verify the analysis and the design method. Note also that a blind analysis contest, like the one in 2007 for

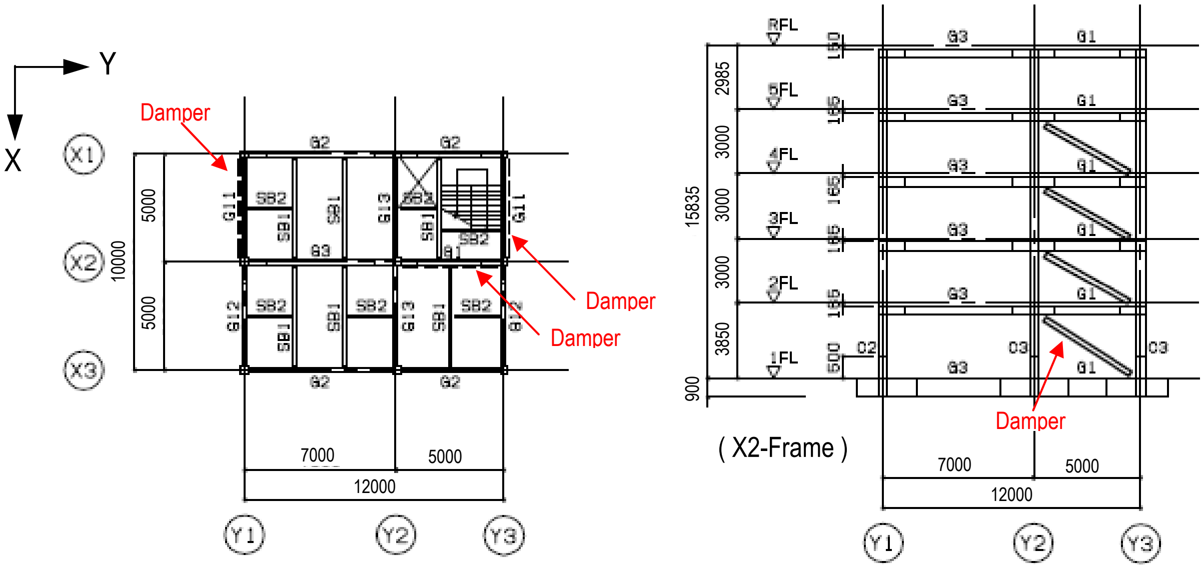


Fig. 1 Full-Scale 5-story Building with Dampers (E-Defense Tests)

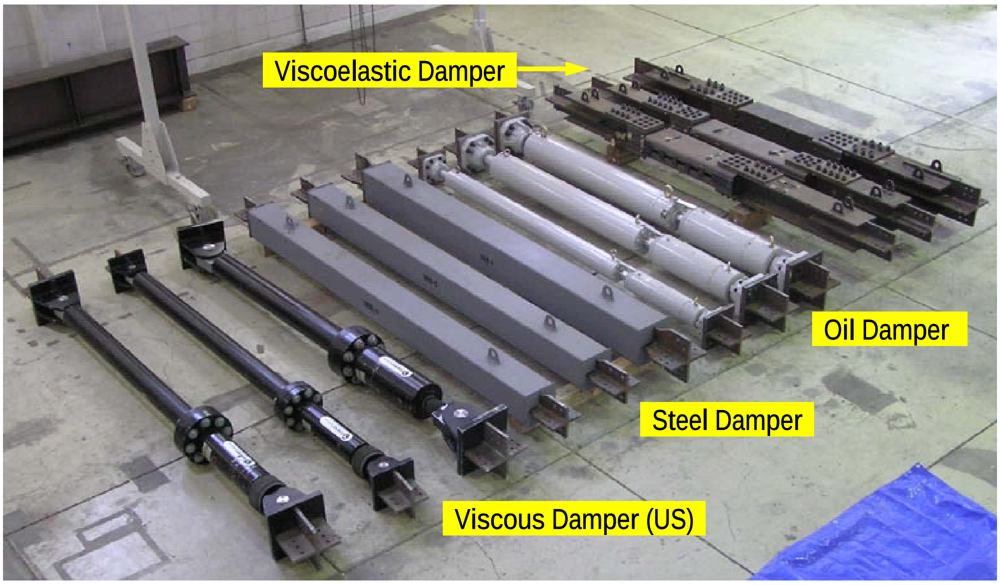


Fig. 2 Full-scale Dampers Tested Prior to Building Experiments

steel building collapse (Ohsaki et al. 2008), will be held as the world-wide competition for the accuracy of analytical prediction prior to the full-scale experiment.

3. CURRENT CODE AND JSSI SPECIFICATIONS

3.1. Japanese Code and JSSI Specifications

The second issue is standardization of the technology and design method. Fig. 3 shows design procedures of steel buildings stipulated by the Japanese code called Building Standard Law, and new options being proposed by Association of New Urban Housing Technology (ANUHT), Japan. For the buildings exceeding 60 meters in height, the code requires time history analyses, design review by the panel members, and special permission by the ministry of land, infrastructure, transport, and tourism (MLIT).

As for the shorter buildings that constitute majority of the building stock in Japan, the designers are allowed to select one of the four methods shown in Fig. 3. However, methods (1) and (2) are intended for conventional structures, and are not suitable for those with dampers. Method (3) includes the so-called energy-balance method that includes only a case using steel dampers. In this manner, the code is not yet providing a simplified method covering all typical damper types.

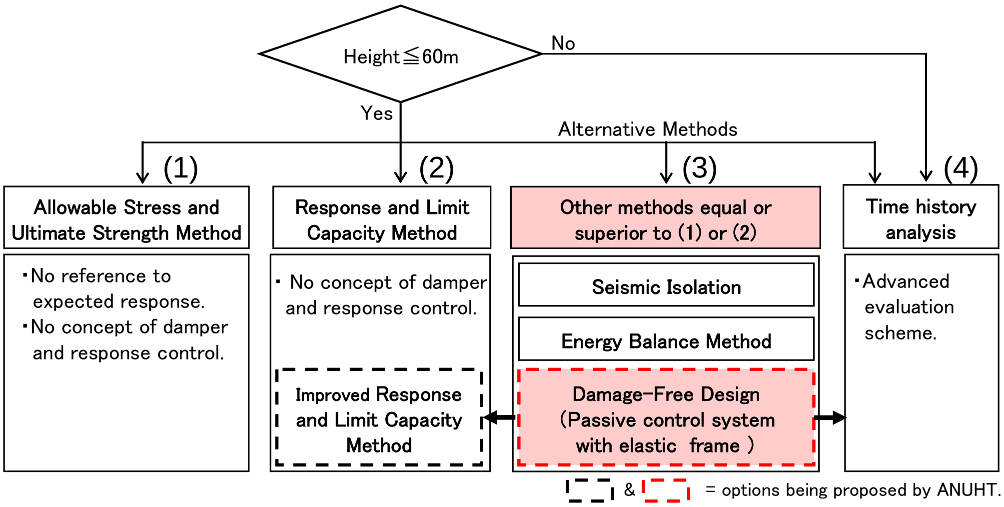


Fig. 3 Current Japanese Code Procedures and Proposed Additions

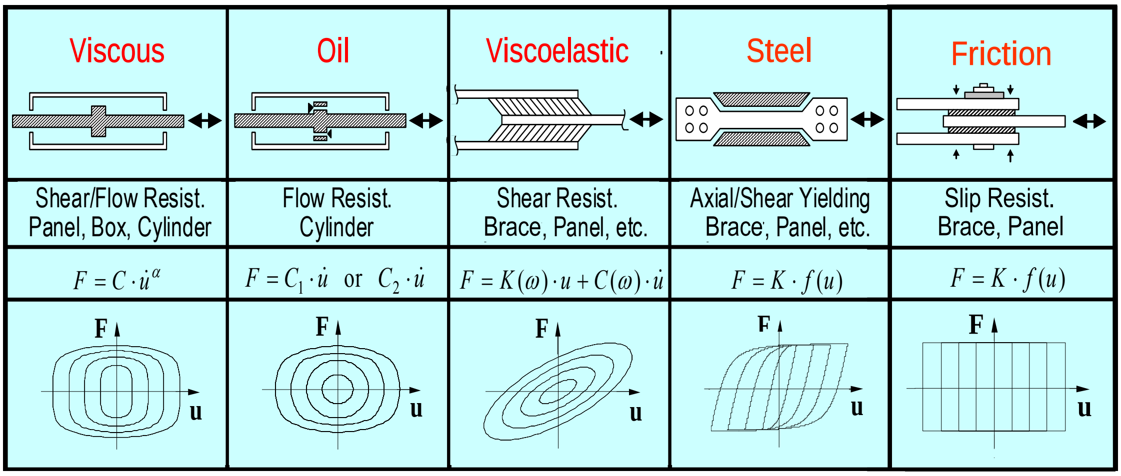


Fig. 4 Five Types of Dampers Considered by JSSI Manual

On the other hand, an accurate and simple design procedure is available from specifications in "Manual for Design and Construction of Passively-Controlled Buildings" that is published by Japan Society of Seismic Isolation (JSSI 2003, 2005, 2007). The researchers in China also produced Chinese translation of the manual (Jiang 2008). The design procedure was originally proposed by Kasai et al. for elastoplastic damper and viscoelastic damper (Kasai et al. 1998). It was then extended to consider more damper types (Fig. 4), a variety of frame configurations (Fig. 5), higher mode effects, and other key items (Kasai et al., 2005, 2006b, 2007b, 2008b). The manual reflects such research findings, and provides the design procedures for five different types of dampers (Fig. 4). The dampers are briefly described below:

The three damper types shown at left of Fig. 4 are velocity-dependant. *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. *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. *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.

The two damper types shown at right of Fig. 4 are deformation-dependant. *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. *Friction damper* utilizes slip resistance between two metallic surfaces, or between metal and friction pad whose material is analogous to that

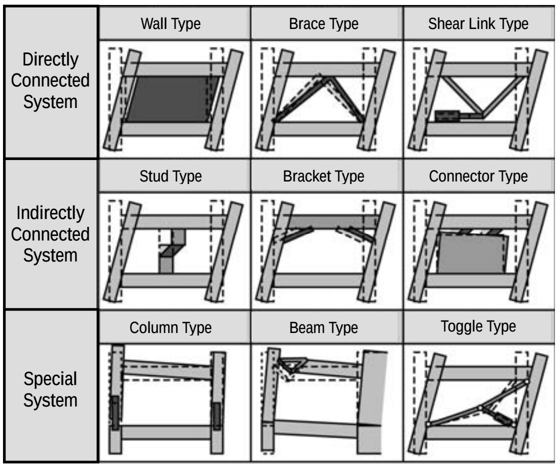


Fig. 5 Various Frame Configurations

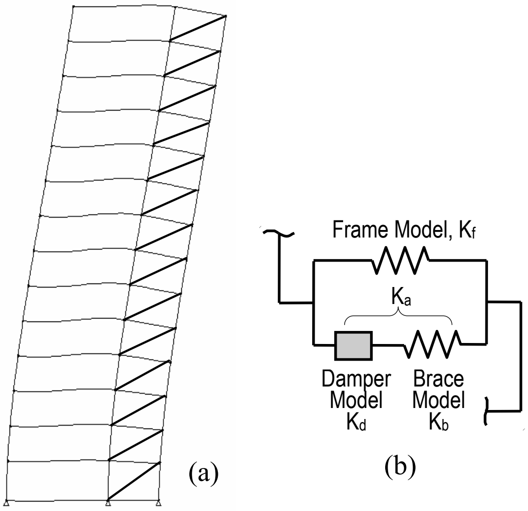
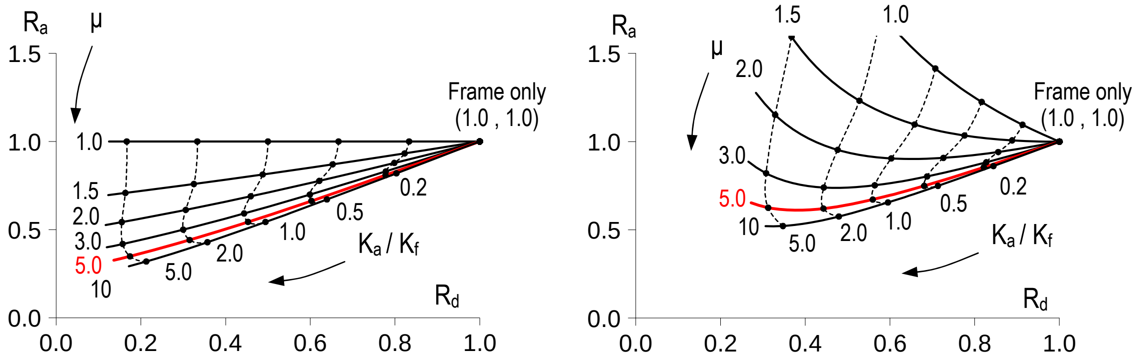


Fig. 6 Shear Beam Modeling for Flexure Behavior



(a) Constant S_{pa} Case (b) Constant S_{pv} Case

Fig. 7 Performance Curve for Steel Damper Case

typically used for a car brake. These elements must be compressed sufficiently to produce the friction force, and the hysteresis is of an ideal rectangle shape.

Various frame types currently used in Japan (Fig. 5) are also considered. For design and efficient time history analyses, they are commonly transformed into a multi-degrees-of-freedom (MDOF) shear beam system such as shown in Fig. 6b, by using a unique transformation method proposed by Kasai and Iwasaki (2006a). The method can create a reasonably accurate shear beam system, even for a frame developing considerable flexural deformation (Fig. 6a). Based on these, and by reflecting as accurately as possible the difference of hysteresis loops among the five damper types, the design procedures for the multi-story passively-controlled building were developed. They will be briefly explained below, by referring to a steel damper type as an example.

3.2. Performance Curves and Direct Design Method for Target Performance

Fig. 7 shows the *performance curves* representing the multi-story building by an equivalent single-degree-of-freedom (SDOF) system. The system may be considered as a single-story system having equivalent frame, damper, and brace like the MDOF system in Fig. 6a. The curves show both *displacement reduction ratio* R_d and *force* (*or acceleration*) *reduction ratio* R_a, which are the values of the peak responses normalized to those without dampers (JSSI 2003, 2005, 2007). The curves are obtained by expressing mathematically the effective vibration period and damping ratio in terms of the balance of the parameters mentioned above, and by combining them with the idealized smooth response spectrum. Fig. 7a assumes the constant pseudo-acceleration spectrum, as often considered in designing short building, and Fig. 7b assumes the constant pseudo-velocity response spectrum, typically considered for moderate to tall buildings.

For the steel dampers considered, K_a/K_f and μ govern the response reduction: the former is a ratio of the added component elastic stiffness to the frame elastic stiffness, and the latter the ductility demand to the added component, where added component is a series combination of the damper and the elastic brace. The curves clearly indicate, and promote understanding of, the strong effects of balance among the frame, damper, and brace. The curves also clearly indicate necessary stiffness ratio of damper or added component relative to the frame, once the target drift and desired ductility demand are specified. Furthermore, the ratio can be applied to size the damper in the MDOF system whose frame stiffness is explicitly known at each story. A special method is also available for assuring reasonably uniform story drift distributions, even when the frame without dampers tends to deform non-uniformly (Kasai et al., 2005, 2006b, 2007b, 2008b).

Note also that the current code provides methods (Fig. 3) to check adequacy of a given structure, thus, the design procedures are iterational, involving redesign and rechecking. In contrast, the method introduced here does not only address wide range of passive control, but also has a significantly different concept. It directly obtains the design solution for a given target performance, and would be more suitable for the performance-based engineering. The method, therefore, will be called the Direct Design Method for Target Performance (DDM).

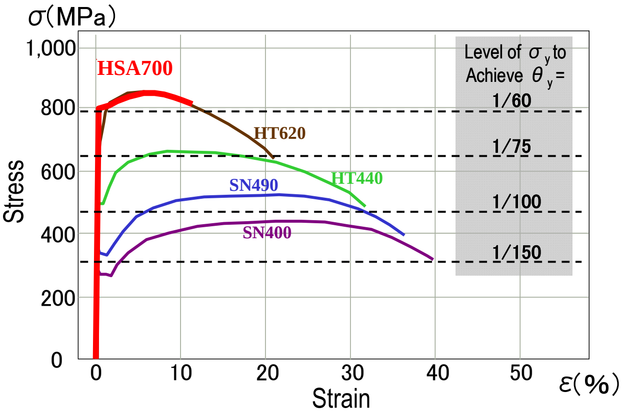


Fig. 8 Super High Strength Steel Considered

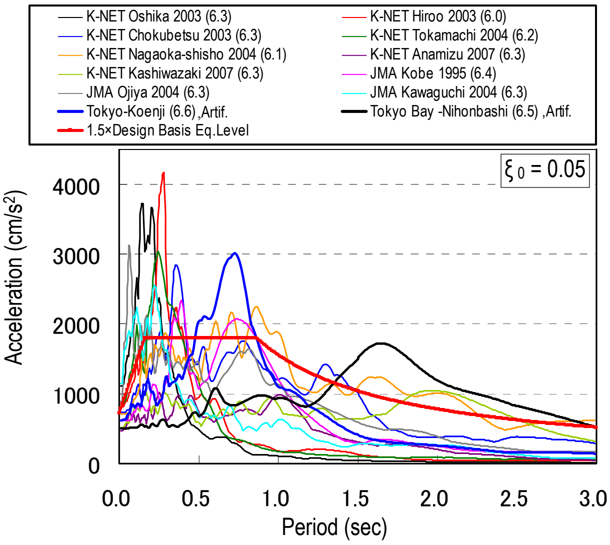


Fig. 9 Catastrophic Earthquakes Considered

4. DEVELOPMENT OF DAMGE-FREE STRUCTURE AND DESIGN SPECIFICATIONS

4.1. Current Development by ANUHT Committees

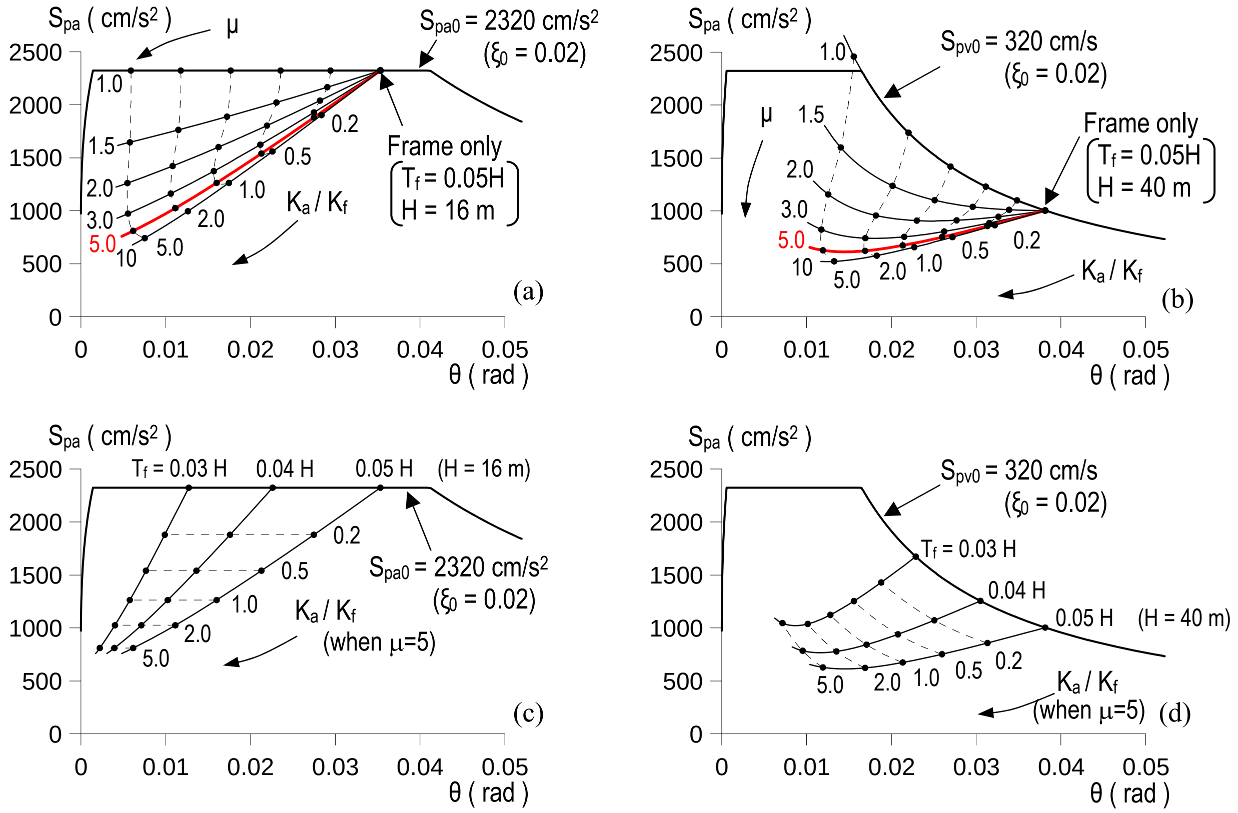
The third issue is extension to damage-free structure and corresponding design specifications. The Japanese government set up a major research/development project, targeting realization of urban infrastructure that is free from damage, even under the catastrophic earthquake. The project has been subcontracted by ANUHT for the period of 2005 to 2009, and has organized a large team of researchers/designers from universities, construction companies, and design firms, in order to develop a new building system using steel dampers and steel frames. The system is expected to be damage-free, against the earthquake of the JMA (Japanese Meteorological Agency) seismic intensity up to 6.4, which is equivalent to the modified Mercalli intensity of about X.

The team investigated into the economical super high strength steel that can be used for the members of the frame. The newly developed steel called HSA700 has the strength more than 800 MPa and is considered to have adequate properties, but other super high strength steel materials are also being investigated. By using this material, the yield drift angle of the frame increases to 1/75 (=0.0133) rad. or more (Fig. 8). As will be explained, the building drift angle will be kept within this limit by using steel dampers.

Fig. 9 shows acceleration response spectra of the ground motions that were recorded during the recent major earthquakes in Japan. The thick and smooth line indicates the design spectrum corresponding to 1.5 times the Japanese design basis earthquake, and it shows the constant acceleration and velocity spectra of 1,800 cm/s^2 and 248 cm/s, respectively, under damping ratio of 0.05. By converting the values to initial damping of 0.02 typically considered for steel building, one obtains the constant values of S_{pa0} = 2,320 cm/s^2 and S_{pv0} = 320 cm/s, which will be used to produce modified performance curves as described below:

4.2. Modified Performance Curves for Direct Design Method

Fig. 10 shows projection of the performance curve shown earlier (Fig. 7). Advantage of this format is that the displacement and acceleration responses are not normalized, and story drift angle and maximum acceleration response are readily found. Straight-line deformed shape of the building is assumed and equivalent height is considered to be $2H/3$, when estimating the drift angle θ. Note that the figure corresponds to a case of selected frame vibration periods T_f and building height H. For other values of T_f and H, the responses shown must be scaled by using the rules indicated in Fig. 10. As a next effort to make the curve more convenient, only the ductility demand $\mu = 5$ will be selected. This is because $\mu \approx 5$ leads to almost the smallest set of story drift and acceleration for a given K_a/K_f value (Figs. 7 and Fig. 10a,b). The modified performance curves are given in Fig. 10c and 10d. The curves can give the designers opportunities to explore combinations of frame and dampers. The conventional steel moment resisting frame tends to show the period $T_f \approx 0.03H$ for a tall building, and increases up to $0.05H$ approximately, as building is shorter. The modified performance curve can



Constant S_{pa} Case :
For other S_{pa0} and H values, θ and S_{pa} will be $\beta_1\beta_2$ and β_1 times, where $\beta_1=S_{pa0}/2320$ and $\beta_2=H/16$.

Constant S_{pv} Case :
For other S_{pv0} and H values, θ and S_{pa} will be β_1 and β_1/β_2 times, where $\beta_1=S_{pv0}/320$ and $\beta_2=H/40$.

Fig. 10 Modified Performance Curve for Convenient Evaluation

propvide different options to meet the target drift angle, i.e., one can use a stiffer (i.e., short period) frame and softer (i.e., smaller) damper, or vice versa. Acceleration will differ between the options (Fig. 10c, d).

4.3. Example for Damage-Free Structure Design

A design of the damage free structure will be briefly described. Fig. 11 shows the acceleration spectra of 7 ground motions considered. The frame is 8-story and its height H = 33 m. The frame vibration period T_f = 1.39 s,. Thus, constant psuedo-velocity and $T_f \approx 0.04H$ will be considered in the modified performance curve of Fig. 10d. Note that the pseudo-velocities of some ground motions exceed the code-specified value of 320 cm/s under damping ratio 0.02 (Fig. 11). Among such motions, an artificial motion that is 2.5 times the BCJ-L2 (Level 2 ground motion given by the Building Center of Japan) shows very smooth spectrum curve of 360 cm/s (Fig. 11). Since the curve can represent somewhat conservative level for all the motions plotted, the design considers S_{pv0} = 360 cm/s, as well as the target drift angle of 1/75 (= 0.0133) rad. mentioned in Sec. 4.1. Thus, $\beta_1 = S_{pv0}/320 = 1.125$ will be used for the performance curve in Fig. 10d.

The actual θ-value will be β_1 times the value in Fig. 10d. Thus, for using the performance curve in Fig. 10d, one can consider $0.0133/\beta_1$ = 0.0118 rad. as the fictitious target angle. Correspondingly, the curve for T_f = $0.04H$ gives $K_a/K_f \approx 2.8$ in Fig. 10d. By converting the K_a/K_f value of the SDOF system to MDOF system, one can obtain the required stiffness of the added component and damper (Fig. 6). From the target drift angle, one obtains the corresponding deformation of the added component, and dividing it by the required ductility demand μ = 5 gives the yield deformation, and consequently the required yield force of the added component.
Fig. 12 shows performance of thus-designed structure. The direct design method (DDM) for the target story drift appears to be reliable. Clearly, the damage-free structure under the catastrophic motion is feasible, as evidenced by the small drift and well-controlled performance shown in Fig. 12.

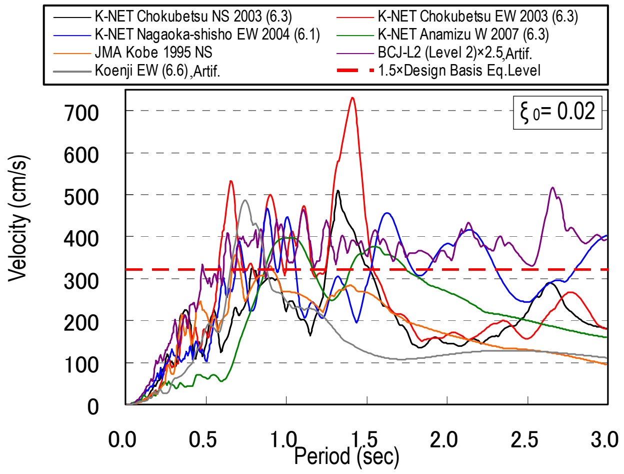


Fig. 11 Velocity Spectra for Seven Ground Motions

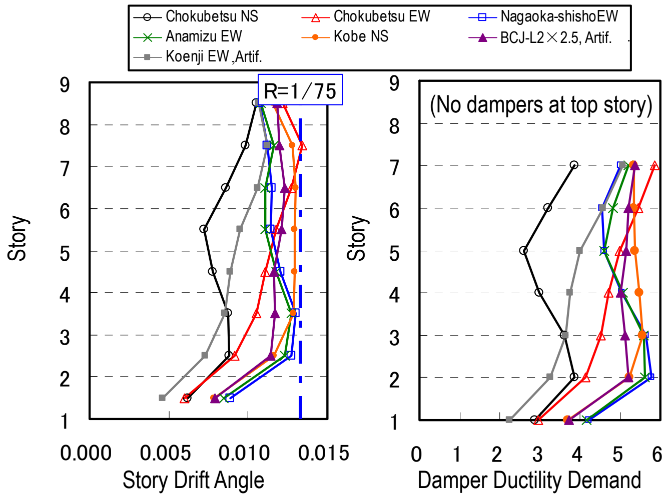


Fig. 12 Performance of Damage-free 9-story Building Designed by Using Performance Curve

5. SUMARRY

This paper has discussed three key issues regarding the current status of passive control technology in Japan. They are; a major full-scale experimental program on passive control of buildings, current situation of the code and specifications on passive control, and new performance engineering and damage-free design using high strength steel and dampers.

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