CURRENT STATUS OF JAPANESE PASSIVE CONTROL SCHEME FOR MITIGATING SEISMIC DAMAGE TO BUILDINGS AND EQUIPMENTS

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Abstract: Due to the recent earthquakes in the U.S. and Japan, many modern buildings ceased functioning and required costly structural and nonstructural repairs, although they successfully protected the lives of the occupants. Because of these, most major buildings constructed after the earthquakes utilize either passive-control scheme or base-isolation scheme in order to better protect the building and its contents. This paper addresses current status of passive control technology being implemented in Japan. Four major groups of dampers and their basic mechanisms are discussed. Three groups of frames are explained, referring to different connection schemes and deformation lags between the frame and damper. A unified approach to assess effectiveness of various dampers and frames will be presented.

1. INTRODUCTION

Passive control scheme has established its status as a viable means to enhance seismic performance of buildings (JSSI 2003, JSCA 2000). In this scheme, the damper connected to the structural frame dissipates the seismic input energy, thereby reducing the kinetic energy and vibration of the building. Japanese desire for adopting this scheme has increased considerably, especially after the recent earthquakes caused serious socio-economical problems in the metropolitan areas of the United States (Northridge) and Japan (Kobe). Due to these earthquakes, many modern buildings ceased functioning and required costly structural and nonstructural repairs, although they successfully protected the lives of the occupants. Because of these, a number of Japanese major buildings constructed after the earthquakes utilize the passive control scheme to better protect buildings and their contents. The number of such buildings increased to about three hundred in the year of 2002, and has been growing rapidly in Japan (e.g., JSCA 2000).

Considering the above circumstances, the writer has been conducting research into various issues for producing passively controlled buildings of high reliability and performance. The writer was also involved in development of design and construction manual of such buildings, leading the Response Control Committee, Japan Society of Seismic Isolation (JSSI). This so-called “JSSI manual” was published recently (JSSI 2003), and refers to mechanism, design, fabrication, testing, quality control, analytical modeling of dampers, as well as design, construction, and analysis of passively controlled buildings. It was developed by more than 50 members who are university researchers, structural designers, and engineers from about twenty damper manufacturing companies.

This paper describes current status of the Japanese passive control technology, including overview of the writer’s research (Kasai et al. 1998-2004) and committee’s accomplishments (JSSI 2003). Some of the issues abovementioned are not included in this paper due to page limitation. Such issues are described in detail in the JSSI Manual (2003).

2. MAJOR DAMPER TYPES

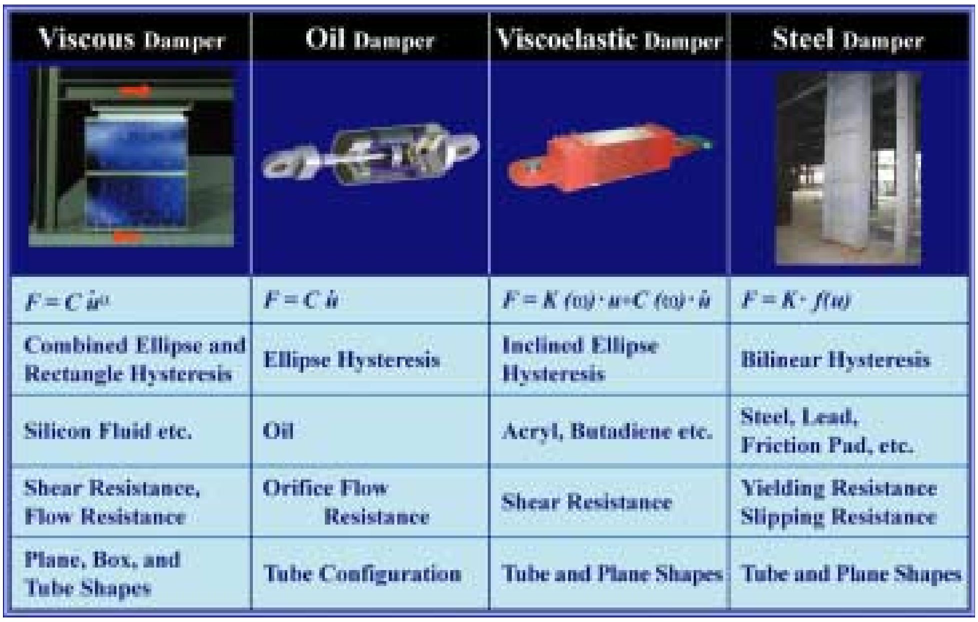
Numerous dampers are being produced and developed in Japan, and they are categorized into four types; oil damper, viscous damper, viscoelastic damper, and steel damper, as shown in Fig. 1.

Viscous damper produces the hysteresis loop of combined ellipse and rectangle. The material used is polymer liquid, and its resistance against flow produces the damper force. The damper possesses configurations of vertical panel, box, or cylinder (Furukawa et al. 2002, JSSI 2003) .

Oil damper produces the hysteresis loop of ellipse. The material used therein is oil, and its resistance against flow at orifice produces the damper force. The damper possesses the configurations of cylinder, and it is usually provided with a relief mechanism that prevents increase in force, making the hysteresis like a rectangle shape (Tsuyuki et al. 2002, JSSI 2003).

Viscoelastic damper produces the hysteresis loop of inclined ellipse. In some material, the hysteresis is close to bilinear especially when it is under large deformation. The material used is polymer composite of acryl, butadiene, silicon, or others, and resistance against loading is produced from the molecular motion. Typical damper has configurations of vertical panel or tube, but it could be designed for many other configurations as well (Okuma et al. 2002, JSSI 2003).

Steel damper produces bi-linear hysteresis. The material is steel, but those using lead or friction pad can exhibit similar behavior. These materials produce elasto-plastic resistance due to yielding or slipping. Typical damper has configuration of vertical panel or tube, but it could be designed for many other configurations as well. This damper is the least expensive among the four types (Nakata .2002, JSSI 2003)



Viscous Damper	Oil Damper	Viscoelastic Damper	Steel Damper
$F = C\dot{u}^{\alpha}$	$F = C\dot{u}$	$F = K(\omega)\cdot u + C(\omega)\cdot\dot{u}$	$F = K\cdot f(u)$
Combined Ellipse and Rectangle Hysteresis	Ellipse Hysteresis	Inclined Ellipse Hysteresis	Bilinear Hysteresis
Silicon Fluid etc.	Oil	Acryl, Butadiene etc.	Steel, Lead, Friction Pad, etc.
Shear Resistance, Flow Resistance	Orifice Flow Resistance	Shear Resistance	Yielding Resistance Slipping Resistance
Plane, Box, and Tube Shapes	Tube Configuration	Tube and Plane Shapes	Tube and Plane Shapes

Figure 1 Major Damper Types

3. MAJOR FRAME TYPES

Figure 2 shows various frame types being used in Japan. The frame types are categorized into directly connected system, indirectly connected system, and special system. More systems are expected to appear in the near future, having better control performance and architecturally superior configurations.

Directly connected system is wall type, brace type, or shear link type. In such a system, the ends of the combined damper and relatively stiff supporting member are connected to the upper and lower floor levels. In other words, the damper is effective in directly controlling the drifts of the frame.

Indirectly connected system is stud type, bracket type, or connector type. In such a system, both ends of the damper are connected to the beams and columns that could deform locally and absorb a portion of the deformations that otherwise could be imposed to the damper. Thus, the damper is generally less effective than those of the directly connected system mentioned above (Kasai and Jodai 2002). However, since the system has an advantage of offering greater freedom for architectural planning, it has been much favored currently by the structural engineers and architects in Japan.

Special system considered herein is either column type or beam type. In such a system, the damper is inserted into intentionally disconnected zone of a beam or a column, and becomes a part of those members. Thus, it does not create any obstacle in the floor plan, but its control effectiveness depends on how rigid the rest of the frame is. Similarly to the indirectly connected system, the frame must be very stiff such that the deformation takes a place in the damper. Kanada et al. (2002) for instance described a real application of the column type, which turned out to be very effective in controlling both displacements and forces including uplift force of the foundation.

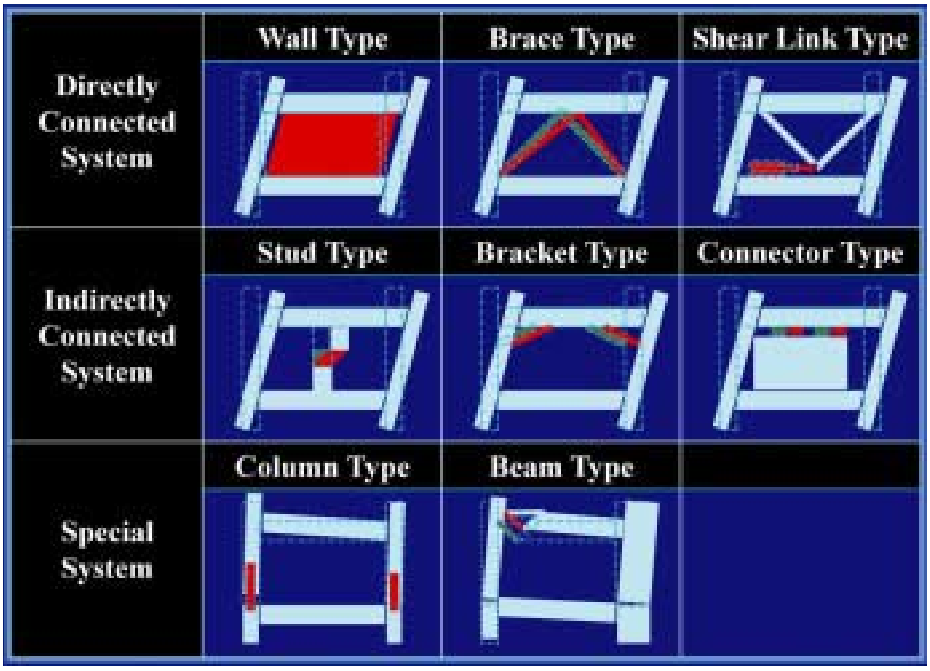


Figure 2 Major Frame Types

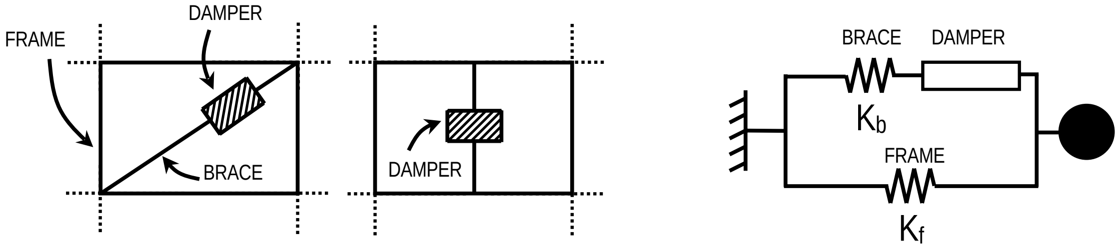
4. UNIFIED MODELING OF VARIOUS SYSTEMS FOR DESIGN

4.1 Model Idealization

Previous chapters described 4 types of dampers and 8 different frames. About 20 combinations of the dampers and frames are used currently in Japan (Kibayashi et al. 2002, JSSI 2003). More combinations are expected, since new dampers and/or frames are being developed in Japan. Thus, it is important to develop common methodology that evaluates various passive control systems having different dampers and frames. Such methodology would enable engineers to understand and directly compare control mechanisms, performance ranges, and element interactions of various systems.

Pursuant to these, the writer proposed a common model to represent properties and characteristics of various passive control systems (e.g., Kasai et al. 1998, Kasai and Okuma 2001b, Kasai et al. 2003c). Figure 3 shows an example, where two distinct systems, directly- and indirectly-connected systems (Chapter 3), are commonly considered as an equivalent SDOF (single-degree-of-freedom) system. The SDOF system consists of damper and supporting member (e.g., brace) connected in series, as well as a frame connected to these components.

As depicted by Figure 3(b), the parameters affecting control are the mass, elastic stiffness of the frame and brace, and damping and stiffness of the damper. As a general term, "*added component*" is defined for the damper and brace connected in series. In this component, the brace deformation can reduce the damper deformation, and consequently energy dissipation. Hence, appropriate modeling of the added component is an essential step toward correct performance evaluation.



(a) Examples of Directly-Connected System and Indirectly-Connected System

(b) Common Idealization for Various Systems

Figure 3 (a) Example Configurations of Passive Control Systems, and (b) Common SDOF Model

Figure 4 shows four added components containing different dampers. The brace is considered to be elastic and its stiffness is defines as K_b. Following comments are given for each added component:

(a) Energy dissipater of s*teel damper* is expressed by an elasto-plastic spring, and its elastic stiffness is defined as K_d. Added component elastic stiffness K_a is expressed simply by K_d and K_b only.

(b) Energy dissipater of *oil damper* is expressed by a bilinear dashpot, and its viscous coefficient C_d switches between high and low values when the "relief load" (Chapter 2) is exceeded. The damper also has elastic stiffness K_d , due to compressive modulus of the oil. Thus, equivalent brace stiffness K_b*, putting K_d and K_b together, is sometimes used for the ease of modeling.

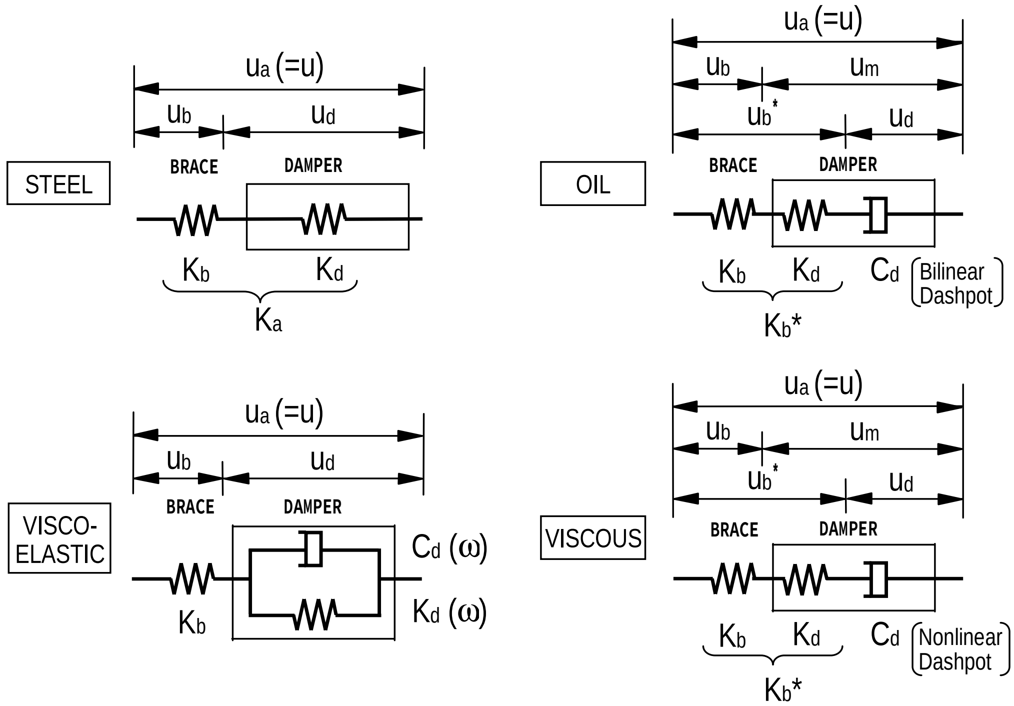


Figure 4 Four Types of Dampers and Added Components

(c) Energy dissipater of *viscoelastic damper* is expressed by a dashpot and a spring connected in parallel. Their viscous coefficient C_d and elastic stiffness K_d, respectively, depend on the excitation frequencies. This added component, unlike others, includes parallel elements, and the brace having elastic stiffness K_b is the only element attached in series.

(d) Energy dissipater of *viscous damper* is expressed by a nonlinear dashpot. The dashpot force equals the viscous coefficient C_d times the fractional power of the velocity. Like the oil damper, it has elastic stiffness K_d due to compressive modulus of the viscous polymer liquid, and equivalent brace stiffness K_b*, putting K_d and K_b together, is sometimes used for the ease of modeling.

Except for a case using steel damper, each of stiffness and damping properties of the added component is expressed by K_d , K_b , C_d , and excitation frequencies.

4.2 Hysteretic Characteristics of Passive Control Systems

Figure 5 shows hysteresis curves of the energy dissipater, added component, and system (including frame), for the cases using four different dampers. Sinusoidal deformation of a given peak deformation magnitude is imposed to each, and the figure plots the steady-state responses.

Note the black dot (●) indicating the point of peak deformation, where the "*storage stiffness*", or so-called equivalent stiffness, is defined as the corresponding force divided by the deformation. Likewise, "*loss stiffness*" is defined as the force at the white dot (○) divided by the peak deformation. From now on, the storage stiffness K_d', K_a', and K', the loss stiffness K_d", K_a", and K" will be considered for the energy dissipater, added component, and system, respectively.

These stiffnesses can be mathematically expressed in terms of K_d , K_b , C_d , and excitation frequencies mentioned in Section 4.1. Based on this, one can determine the forces at the peak and zero displacements, respectively, and subsequently the peak force, energy dissipated, deformation lag and magnitudes at each component, making evaluation of the control system possible.

Energy dissipater of the *viscous damper*, when its force for instance is proportional to 0.4th power of velocity (Section 4.1), exhibits hysteresis of a rectangle shape with round corners. The force is relatively large at small deformation, resulting in almost rigid response of the dissipater. At large deformation, the force is almost bounded, preventing overstress of the damper, connections, and surrounding members. Added component deforms more and shows diametrically longer hystresis loop (Figure 5) because of the elastic springs (Figure 4), and develops non-zero storage stiffness unlike the dissipater. As for the system, its storage stiffness is sum of those of the added component and the frame due to their parallel combination, whereas the loss stiffness equals that of the added component, since the frame is considered to be elastic (Kasai et al. 2003c, JSSI 2003).

Energy dissipater of the *oil damper* shows an elliptical hysteresis curve at small deformation and almost a rectangle shape at large deformation. It produces the force of a relatively high magnitude at small deformation, but it does not behave as rigid as the viscous damper mentioned above. The trends of storage and loss stiffnesses of the added component as well as system are similar to those observed from the case of viscous damper (JSSI 2003, Kasai and Nishimura 2004d).

Energy dissipater of the *viscoelastic damper*, when it is a linear type as shown (Sec. 3.1), exhibits hysteresis of an inclined ellipse. Unlike the nonlinear dampers above, the shape of the hysteresis remains the same regardless of the peak deformation, which makes dissipater's force unbounded and storage and loss stiffnesses constant. The hysteresis of the added component is more slender due to the spring attached (Figure 4), and the storage and loss stiffnesses are smaller than those of the dissipater. As for the system, its storage stiffness is sum of those of the added component and the frame, whereas the loss stiffness equals that of the added component (Kasai et al. 1998, Kasai and Okuma 2001b, 2002a, JSSI 2003).

The energy dissipater of the *steel damper* exhibits hysteresis of a parallelogram shape approximately. Refined modeling of the hysteresis and its dependency on the strain rate will be given in the near future. In contrast to the other dampers, the dissipater does not absorb energy during small deformation. At large deformation, it absorbs energy by yielding of the material, cumulating damage to the material. Therefore, unlike the other dampers, effect of such damage must be considered when using this damper. This does not, however, prohibit the use of the steel damper, since it can sustain large number of inelastic cyclic excursions when adequately detailed, and it is inexpensive than other dampers. The trends of storage and loss stiffnesses of the added component and system are similar to those observed from the case of the viscous damper (Kasai et al. 1998, Kasai et al. 2003b, JSSI 2003).

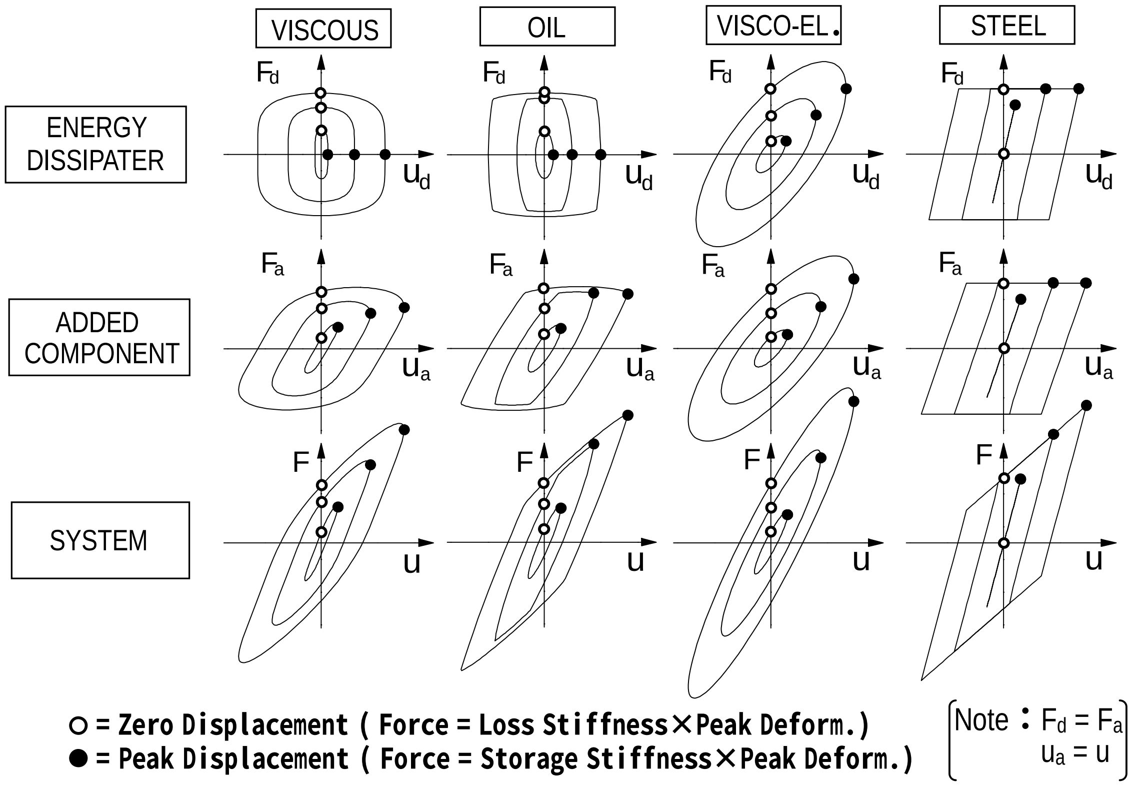


Figure 5 Steady-State Responses of Energy Dissipaters, Added Components, and Systems for 4 Different Dampers and 3 Different Peak Deformations

5. PERFORMANCE CURVES AND DESIGN

5.1 Use of Storage Stiffness and Loss Stiffness

To date, design and performance prediction of passive control systems have typically been based on iterations involving extensive response time history analyses or equivalent static analyses using various types and sizes of dampers. The analysis methods are also different between the various systems; these make direct comparison of the systems difficult. Moreover, they offer limited information about the possible range of seismic performance variations and the complex interactions between the dampers, their supporting members, frame, seismic input, and response.

Using mathematical expressions for the storage stiffness and the loss stiffness (Section. 4.2), the writer developed formulas to evaluate dynamic properties and responses for different dampers and systems. Based on this and using idealized seismic response spectra, the writer also proposed a method to commonly express the seismic peak responses of systems and local members by a continuous function of the structural and seismic parameters. The method promotes understanding of the commonalities and differences between various systems having distinct energy dissipation mechanisms. It requires only simple calculations, and its prediction agrees well with the results of the extensive multi-degree-of-freedom dynamic analyses performed.

Figure 6 shows examples for evaluating multi-story passive control systems using the four types of dampers mentioned in Chapters 2 and 4. The curves are named as *performance curves* which model buildings as an equivalent SDOF system explained in Sec. 3.1. The curves show both *displacement reduction ratio* R_d and *force* (*or acceleration*) *reduction ratio* R_a that are defined as the values of the peak responses normalized to those having no dampers (e.g., Kasai et al. 1998, JSSI 2003). In these examples, pseudo-velocity response spectrum is assumed to be constant over different periods, as often considered when designing moderate to tall buildings. The response reduction ratios appear to vary widely, depending on balance among the frame, the damper, and the supporting member such as a brace. Note the following for each figure:

(a) When using steel *dampers*, 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 is a ductility ratio of the system.

(b) When using *oil dampers*, K_{d1}" $/K_f$ and K_b/K_f govern the response reduction. The former is a ratio of the dissipater loss stiffness (defined when peak force is below the relief load) to the frame elastic stiffness, and the latter is a ratio of the brace elastic stiffness to the frame elastic stiffness. Relief load of the dissipater (Section 4.1) is already set optimum in the curves.

(c) When using *viscoelastic dampers*, K_d"$/K_f$ and K_b/K_f govern the response reduction. The former is a ratio of the dissipater loss stiffness to the frame elastic stiffness, and the latter is a ratio of the brace elastic stiffness to the frame elastic stiffness.

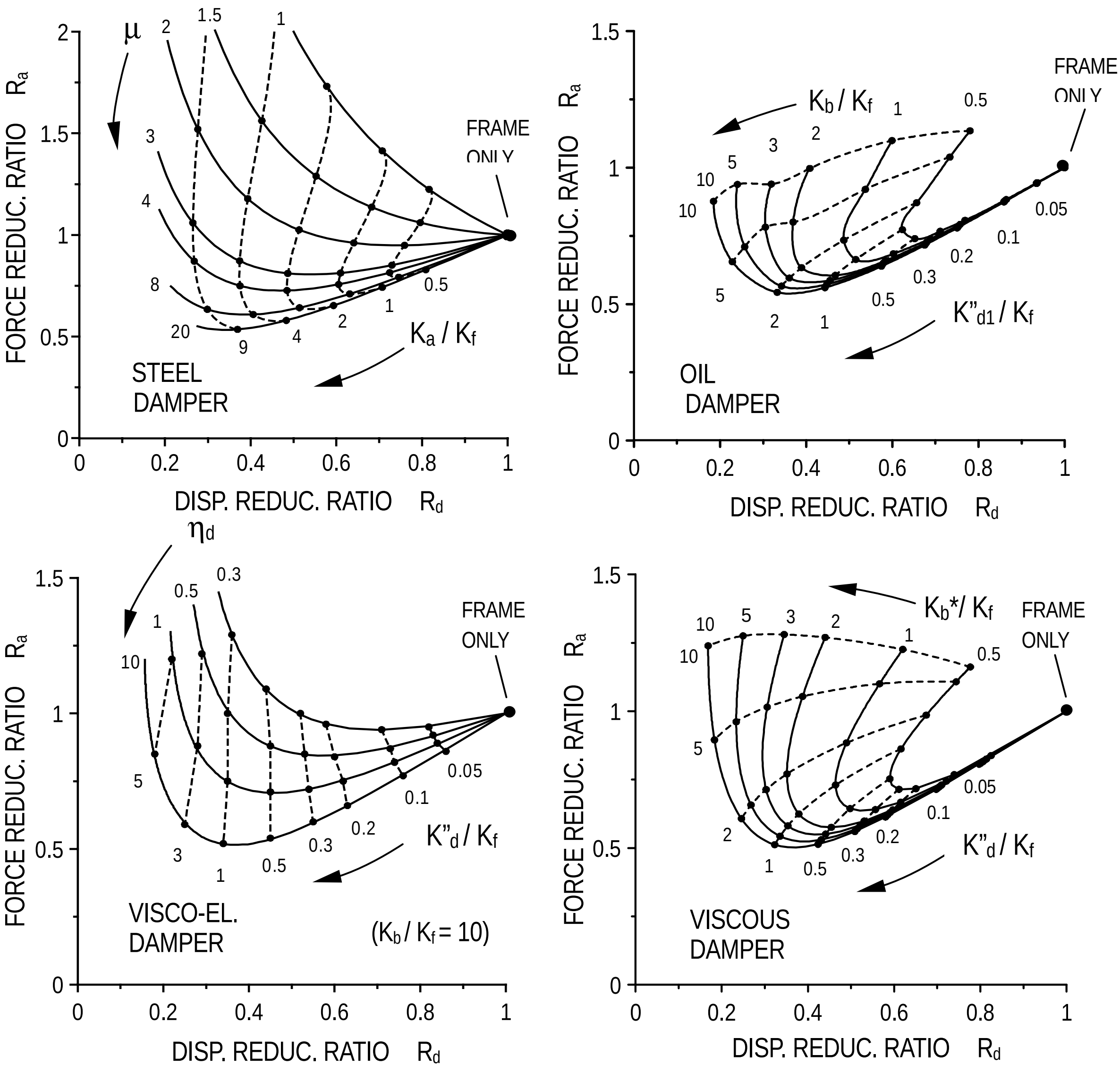


Figure 6 Performance Curves for Passive Control Systems Using 4 Different Damper Types

(d) When using *viscous dampers*, $K_d"/K_f$ and K_b^*/K_f govern the response reduction. The former is a ratio of the dissipater loss stiffness to the frame elastic stiffness, and the latter is a ratio of the equivalent spring stiffness to the frame elastic stiffness. The equivalent spring stiffness is obtained from the damper elastic stiffness and brace elastic stiffness (Figure 4). The curves plotted in Figure 6 are for a case where dissipater force is proportional to 0.4th power of velocity.

Figure 6 enables the users to quickly evaluate response reduction: To a certain extent, larger damper leads to more reduction of displacement and force. However, excessively large damper appears to be ineffective for displacement control, and detrimental in force control, as observed from sharply rising curves. Figure 6 also shows decrease of control effectiveness by smaller brace stiffness: brace deforms more, and damper deformation as well as energy dissipation becomes smaller.

5.2 Design of Passive Control Systems

The performance curves (Figure 6) can be used effectively for determining necessary sizes of damper and brace for the required performance. For instance, given an earthquake input of a smooth response spectrum, the peak displacement and base shear of the frame prior to damper installment can be predicted easily from the response spectrum. Then, one can estimate target reduction ratios of displacement and base shear based on the required performance. Considering the target reduction ratios and the performance curve, one can determine the necessary stiffness of the damper and brace. Optimum design solution to control both displacement and force can also be found from the performance curve.

This design result for the SDOF system (Figure 3) can be equally applied to sizing of the dampers in the multistory case as well. That is, one could size the damper and brace such that the ratios of their stiffnesses to the frame story stiffness satisfy the ratios determined from the SDOF approach explained above. When modeling the MDOF frame by the SDOF system, one could use the first mode effective mass approximately equal to 0.8 times total mass for a regular building, and effective height based on the static deflected shape of the frame.

Since the steel damper, viscoelastic damper, and some of the viscous dampers possess considerable storage stiffness, they could be used to tune the storage stiffness of the system at each story level. This can result in the MDOF system having adequate overall storage stiffness distributions throughout the building height. The technique is useful when the frame has undesirable stiffness distributions and tendency to suffer from concentration of deformation at particular story levels. It has been proved to assure relatively uniform story drift distributions in spite of the undesirable frame stiffness distributions (e.g., Kasai et al. 1998, JSSI 2003).

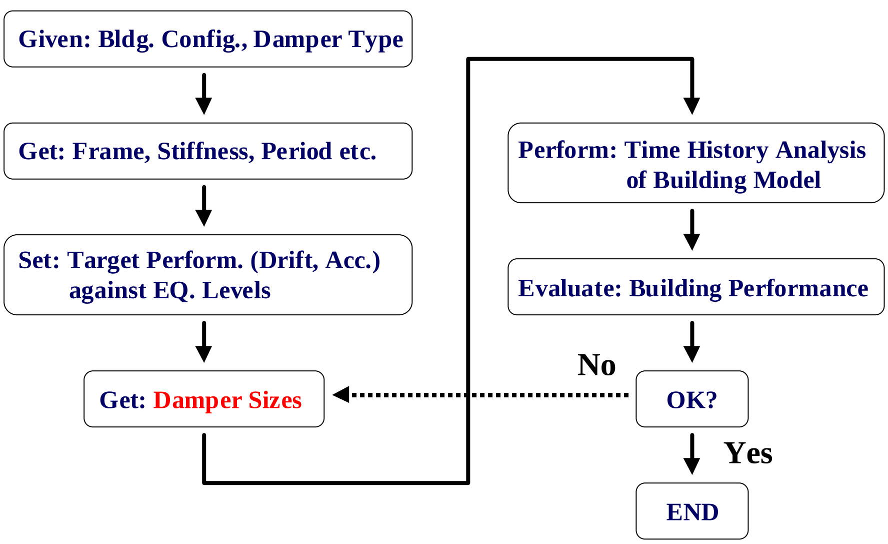


Figure 7 Summary of Damper and System Design Procedures

After completion of design, one can create a MDOF analytical model, and perform time-history analyses using appropriately selected ground motions. Analytical results will be used to confirm or make modifications in design. Fig. 5 summarizes the design procedures. Numerous examples and details for the design procedures are documented in the JSSI manual (2003).

6. TIME HISTORY ANALYSIS AND DISSEMINATION OF COMPUTER CODES

In Japan, significant progress is being made in numerical modeling of the dampers (Figures 1, 4, and 5) for time-history analysis of passively controlled systems. However, the new models, in spite of enhanced accuracy and efficiency, have not necessarily been implemented into the computer programs of software companies or construction companies.

The writer and JSSI members, therefore, intended to accelerate implementations, by publishing model algorithms and computer codes. This should lead to more reliable and fair assessment of the passive scheme, thereby promoting sound growth in the technology. In general, proposed analytical elements simulate the added components (Fig. 4) rather than dampers alone. Such modeling is advantageous for reducing the degree of freedom as well as maintaining numerical stability. The following briefly describes the models, and detailed information can be found from the references.

The element involving *oil damper* rests the viscous coefficient of energy dissipater to a small value when subjected to a large deformation rate, in order to simulate the relief mechanism explained in Section 4.1 (Takahasi and Sekiguchi 2002, JSSI 2003).

The element involving *viscous damper* uses, unlike the oil damper above, a nonlinear dashpot whose force is a fractional power of deformation rate (Oohara and Kasai 2002, JSSI 2003) For some types possessing elastic stiffness, the model considers an in-series combination of the spring and the nonlinear dashpot (Sekiguchi and Takahashi 2002, JSSI 2003). The elastic stiffness may be a nonlinear function of the deformation. Sensitivity against temperature must be modeled for some types.

The element involving *viscoelastic damper* could be either linear type, softening type, and stiffening type. Hysteresis loops of the three types show commonly an inclined ellipse at relatively small deformation, but they differ considerably at larger deformation. In order to simulate this and sensitivities against frequency and temperature, some models consist of in-series as well as parallel combinations of dashpots and springs (Kasai and Okuma 2001b, 2002a, JSSI 2003), and another model directly expresses the constitutive equation of the damper using fractional time-derivatives of the force and deformation (Kasai et al. 2001a, 2002e, 2003a, Ooki et al. 2002, JSSI 2003).

The element involving *steel damper* is proposed by utilizing the constitutive equations of steel material readily known from the past research (Ono et al. 2002), in contrast to the typical Japanese model assuming purely bi-linear behavior. The analysis results must be cross-referenced to cumulative damage of the damper, since the damper is typically designed to yield under the small and frequent seismic loads. Special model is developed for some dampers designed to a post-buckled range.

7. CONCLUSIONS

Passive control scheme has established its status as a viable means to enhance seismic performance of buildings. For the sake of further growth in this technology, it is necessary to promote understanding of the passive control schemes, as well as to create a uniform basis for assessment of the various stages to be followed during the design and construction process.

Pursuant to this, the writer and JSSI Response Control Committee have formulated Design and Construction Manual for Passively-Controlled Buildings (JSSI 2003). The committee consists of more than fifty members who are the researchers from universities and research institutes, the designers from general construction companies and design offices, and the engineers from more than twenty device manufacturing companies.

Due to these efforts, various issues regarding Japanese passive control technology have been documented. Such issues are mechanism, design, fabrication, testing, quality control, and analytical modeling of various passive control devices, as well as design, construction, and analysis of passively controlled buildings. This paper has given brief overview of design and analysis part of the manual. More detailed information can be obtained from the writers' papers as well as the Manual. Furthermore, the abovementioned issues not discussed in this paper are described in detail in the Manual.

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