



## **JSSI MANUAL FOR BUILDING PASSIVE CONTROL TECHNOLOGY PART-1 MANUAL CONTENTS AND DESIGN/ANALYSIS METHODS**

**Kazuhiko KASAI<sup>1</sup> and Masahito KIBAYASHI<sup>2</sup>**

### **SUMMARY**

Japan Society of Seismic Isolation (JSSI), a key organization for promotion and codification for the base-isolation scheme in Japan, began a new activity regarding passive control scheme by forming the Response Control Committee in 2000. The committee published the Manual for Design and Construction of Passively-Controlled Buildings in October 2003. This paper (Part 1) briefly explains the committee, its subcommittees, and working groups, as well as manual contents, mechanisms of dampers and frames, and design and analytical methods. A companion paper (Part 2) summarizes remaining portion of the manual, and subsequent papers (Parts 3 to 12) provide examples for the subjects described in the manual.

### **INTRODUCTION**

Passive control scheme has established its status as a viable means to enhance seismic performance of buildings [1-32]. 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. In Japan, social desire for adopting this scheme as well as base isolation scheme has increased considerably after the 1995 Kobe earthquake. According to the survey conducted by the Japan Structural Consultants Association (JSCA), the number of passively controlled buildings increased to about three hundred in the year of 2002 [2]. 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. Considering the above circumstances, the writers have been conducting research into various issues for passively controlled buildings of high reliability and performance [1-18].

Japan Society of Seismic Isolation (JSSI), a key organization for promotion and codification for the base-isolation scheme in Japan, also initiated a new activity with the writers regarding passive control scheme: JSSI Response Control Committee formed in 2000 and led by the writers made an extensive effort to formulate the “Manual for Design and Construction of Passively-Controlled Buildings” [1]. This so-called “JSSI manual” was published in October 2003, and refers to the mechanism, design,

---

<sup>1</sup> Professor, Structural Engineering Research Center, Tokyo Institute of Technology, Japan. Email: kasai@serc.titech.ac.jp

<sup>2</sup> Takenaka Corporation, Tokyo, Japan. E-mail: kibayashi.masahito@takenaka.co.jp

fabrication, testing, quality control, and analytical modeling of various types of passive control devices, as well as design, construction, and analysis of passively controlled buildings. It was developed by more than 50 members who are the university researchers, the structural designers, and the engineers from about twenty damper manufacturing companies.

This paper (Part 1) briefly explains background and scopes the JSSI manual, the committee, its subcommittees and working groups, as well as manual contents, mechanisms of dampers and frames, and design and analytical methods. A companion paper (Part 2) summarizes remaining portion of the manual, and subsequent papers (Parts 3 to 12) provide examples for the subjects described in the manual. The manual is originally written in Japanese, and will be translated into English and other languages this year.

## **BACKGROUND AND SCOPES**

In order to justify the use of passive control for producing higher seismic performance, it has become necessary to indicate the control effectiveness as well as expected performance to the building officials, owners, and/or users. In this regard, it is necessary to develop a common standard for design, construction, and quality for this technology. The JSSI manual is intended to provide such a standard.

However, such development requires a great caution, since the history of implementing passive control is short. This new system has experienced neither a major earthquake nor frequent minor earthquakes, and database for actual performance is poor. In addition, it is not yet exposed to the long-term use, and durability of the device as well as frame has not been attested in the actual environment. Moreover, analysis and performance prediction are based on the extrapolation of limited experimental data that are typically created from testing of reduced-scale devices and systems under highly idealized load and boundary conditions.

The JSSI manual was developed considering the above-mentioned circumstances. It clarifies the ranges of the device and system performance, as well as limitations of the analysis and prediction methods as precisely as possible. Furthermore, the manual describes broadly the important matters to examine in each stage of a design, manufacture, and construction of various components of the system. In this manner, the manual is expected to promote mutual understanding and common recognition by the structure designer, manufacturer, and builder, which could result in better assurance for the stipulated performance of a building.

Note also that the manual does not intend to restrain the new idea about passive control, and it aims at offering the basis needed to enable flexible and creative thinking on application of the technology.

## **JSSI RESPONSE CONTROL COMMITTEE**

JSSI established the Response Control Committee in February, 2000, for the purpose of investigating and exchanging information on various types of response control schemes such as active, passive, and base isolation systems. Since then, this committee has been growing, and as indicated in Table 1, it currently consists of 3 subcommittees and 8 working groups of more than 50 members. The passive control subcommittee, device standard subcommittee, and their 8 working groups are developing the manual currently (Table 1). The task is a combined effort by the researchers, structural engineers, and device manufacturers.

**Table 1 JSSI Response Control Committee, Subcommittees, and Working Groups**

<i>Committee</i>	<i>Subcommittee</i>	<i>Working Group</i>
Response Control	Active Control	----
	Passive Control	Passive Device Analysis
		Passive System Analysis
		System Design Methodology
	Device Standard	Oil Damper
		Viscous Damper
		Viscoelastic Damper
		Steel Damper
		Device Design

## **CONTENTS OF JSSI MANUAL**

Following summarizes contents of the manual:

### **Chap. 1 General**

Definitions and Terminology, Classifications of Passive Control Systems, Performance Parameters of Control Devices, Applicability of Manual Contents.

### **Chap. 2 Target Control Performance**

Earthquake Damage and Target Performance. Performance Grades of Passive Control System.

### **Chap. 3 Mechanism of SDOF Passive Control System**

Effective Period and Effective Damping Ratio, Steel Damper, Oil Damper with Relief Mechanism, Viscoelastic Damper, Viscous Damper, Simplified Response Prediction Utilizing Response Spectra, Use of Performance Curves.

### **Chap. 4 Design of MDOF Passive Control System**

Mechanism of MDOF Passive Control, Layout of Control Devices, Design of MDOF Systems Using Steel Dampers, Oil Dampers with Relief Mechanism, Viscoelastic Dampers, and Viscous Dampers. Simplified MDOF Response Prediction Based on Static Equivalent Forces.

### **Chap. 5 Time History Analysis Methods for Passive Control Devices**

Analytical Models for Steel Dampers, Oil Dampers with Relief Mechanism, Viscoelastic Dampers, and Viscous Dampers. Numerical Algorithms and Example Subroutines, Comparison with Experiments, Evaluation of Damper Analytical Models in Current Commercial Software.

### **Chap. 6 Time History Analysis Methods for Passive Control Systems**

Member-to-Member Models, Shear Beam Model, Shear-Flexure Beam Model, Modeling Combined Effect of Device and Supporting Member, Comparison of Time History Analysis Results.

### **Chap. 7 Characteristics and Design of Oil Dampers**

Characteristics and Applicable Performance Range, Test and Evaluation Methods, Limit Condition and Design of Device, Limit Condition and Design of Connection Elements.

Chap. 8 Characteristics and Design of Viscous Dampers

Characteristics and Applicable Performance Range, Test and Evaluation Methods, Limit Condition and Design of Device, Limit Condition and Design of Connection Elements.

Chap. 9 Characteristics and Design of Viscoelastic Dampers

Characteristics and Applicable Performance Range, Test and Evaluation Methods, Limit Condition and Design of Device, Limit Condition and Design of Connection Elements.

Chap. 10 Characteristics and Design of Steel Dampers

Characteristics and Applicable Performance Range, Test and Evaluation Methods, Limit Condition and Design of Device, Limit Condition and Design of Connection Elements.

Chap. 11 Declaration and Examinations of Device Properties

Device Performance Specifications, Device Performance Examinations.

Chap. 12 Quality Control Scheme

Manufacturing Process and Quality Control Scheme, Items Subjected to Examinations, Examinations Prior to Delivery, Installation, and Project Completion.

Chap. 13 Operation Scheme during Construction

Operational Attentions, Protection and Curing During Operation, Checking Items for Connection Elements.

Chap. 14 Maintenance Scheme

Basic Agreement, Durability of Device and Connection Elements, Maintenance Plans.

Appendix-1 Examples for Constructed Passive Control Systems

Appendix-2 Design/Analysis Examples of Realistic Multi-Story Frames (JSSI Theme Structures)

Appendix-3 Technical Data Sheets for Dampers Produced by Each Company

Appendix-4 US Standards for Design and Analysis of Passive Control Systems

Appendix-5 Nomenclature

## MAJOR DAMPER TYPES

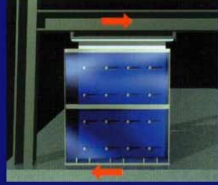



Numerous dampers are being produced and developed in Japan, and the manual categorize them into four types; oil damper, viscous damper, viscoelastic damper, and steel damper, as shown in Figure 1.

*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 [1, 30].

*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 [1, 29].

*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 [1, 31].

*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 [1, 32].

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**

## 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 [9]. 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. [23] 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.

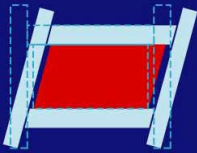
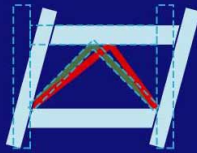
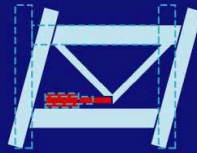
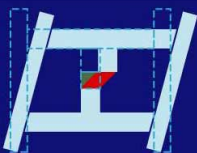
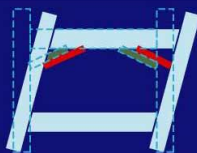
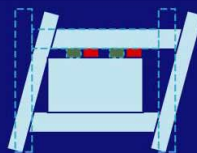
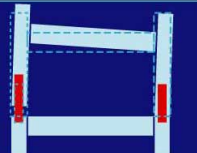
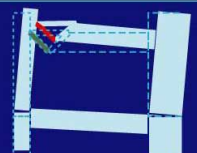
	Wall Type	Brace Type	Shear Link Type
Directly Connected System			
Indirectly Connected System	Stud Type	Bracket Type	Connector Type
			
Special System	Column Type	Beam Type	
			

Figure 2 Major Frame Types

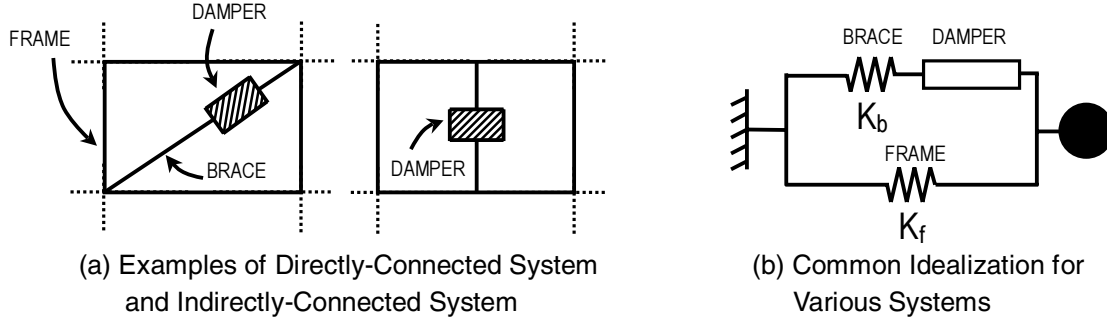
## UNIFIED MODELING OF VARIOUS SYSTEMS FOR DESIGN

### 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 [1, 19, 20]. 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., 3, 4, 6, 14]. Figure 3 shows an example, where two distinct systems, directly- and indirectly-connected systems, 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.

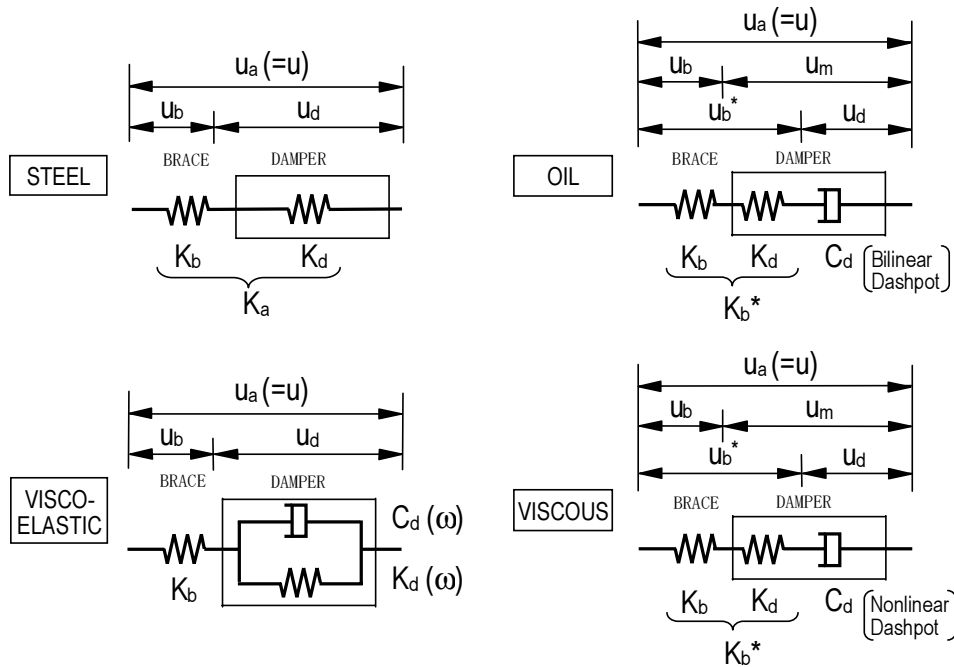
As depicted by Figure 3(b), the parameters affecting control are the mass, elastic stiffness of the frame and brace, and damping and stiffness of the damper. As a general term, “*added component*” is defined for the damper and brace connected in series. In this component, the brace deformation can reduce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



**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 defined as  $K_b$ . Following comments are given for each added component:

- Energy dissipater of *steel 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.
- 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” 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.
- 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.
- 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.



**Figure 4 Four Types of Dampers and Added Components**

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.

### 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 the previous section. 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 (previous section), 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 hysteresis 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 [1, 14].

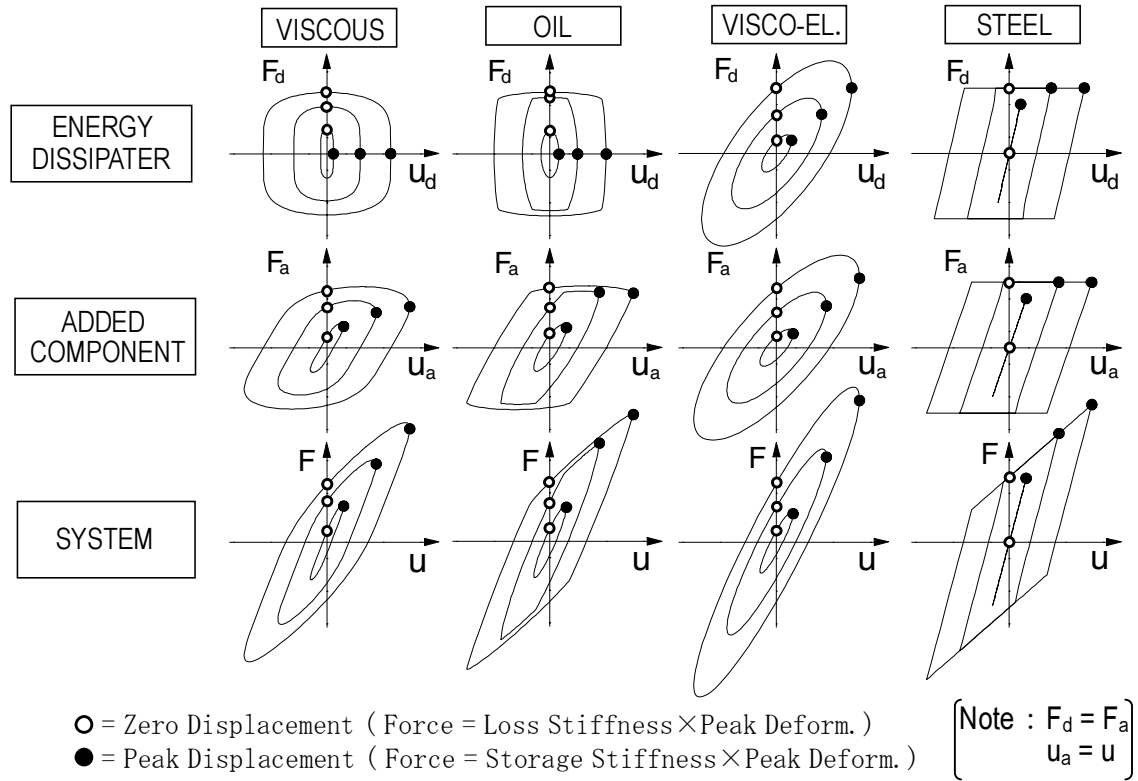
Energy dissipater of the *oil damper* shows an elliptical hysteresis curve at small deformation and almost a rectangle shape at large deformation. It produces the force of a relatively high magnitude at small deformation, but it does not behave as rigid as the viscous damper mentioned above. The trends of storage and loss stiffnesses of the added component as well as system are similar to those observed from the case of viscous damper [1, 18].

Energy dissipater of the *viscoelastic damper*, when it is a linear type as shown, 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 [1, 3, 4, 6, 7].

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 [1, 3, 4, 13].



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

## PERFORMANCE CURVES AND DESIGN

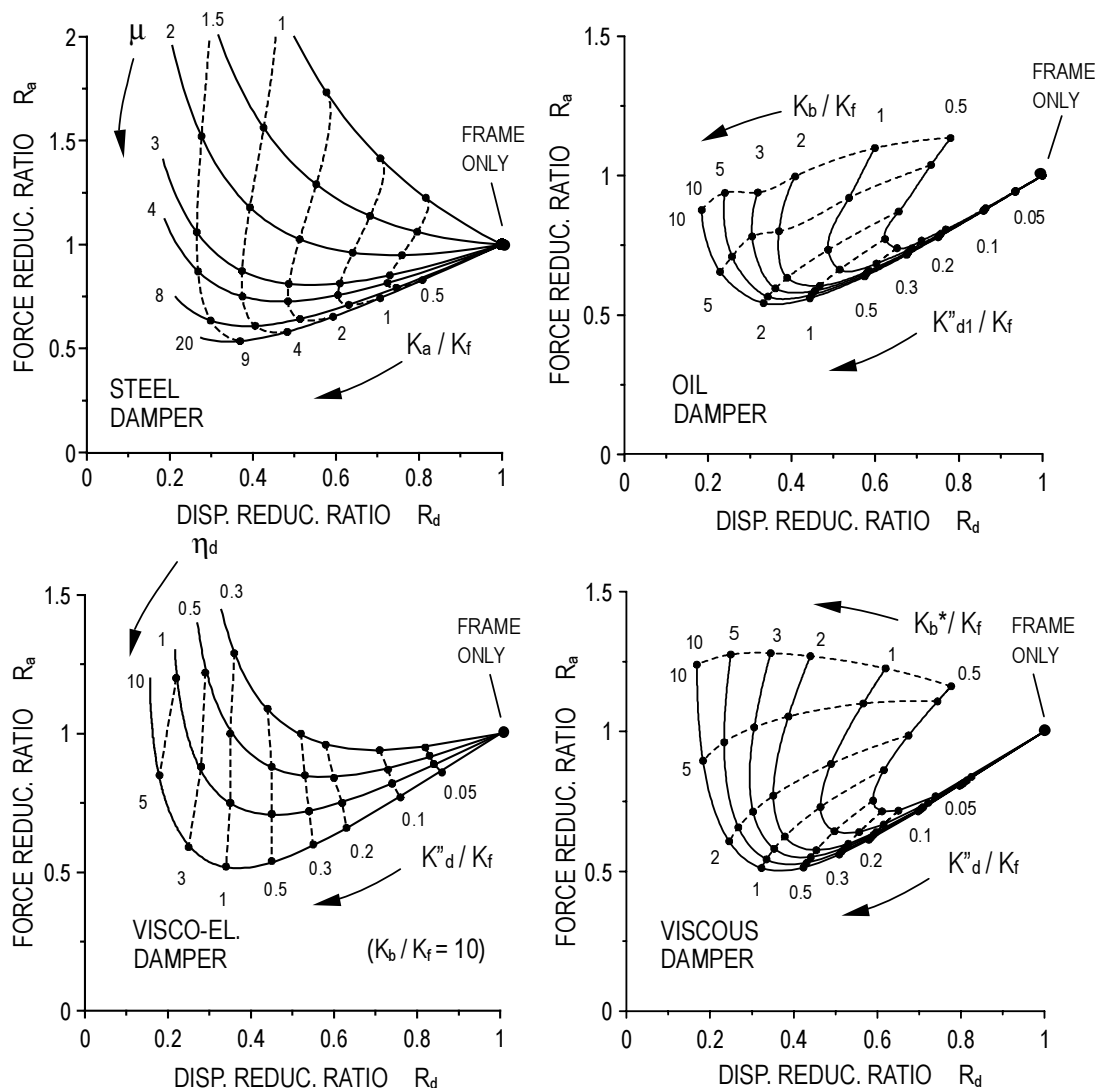
### Use of Storage Stiffness and Loss Stiffness

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 (previous chapter), 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 earlier. The curves are named as *performance curves* which model buildings as an equivalent SDOF system explained in earlier. 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., 1, 3, 4]. 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:

- When using *steel dampers*,  $K_d/K_f$  and  $\mu$  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.
- 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 is already set optimum in the curves.



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

- (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.
- (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.

### 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.

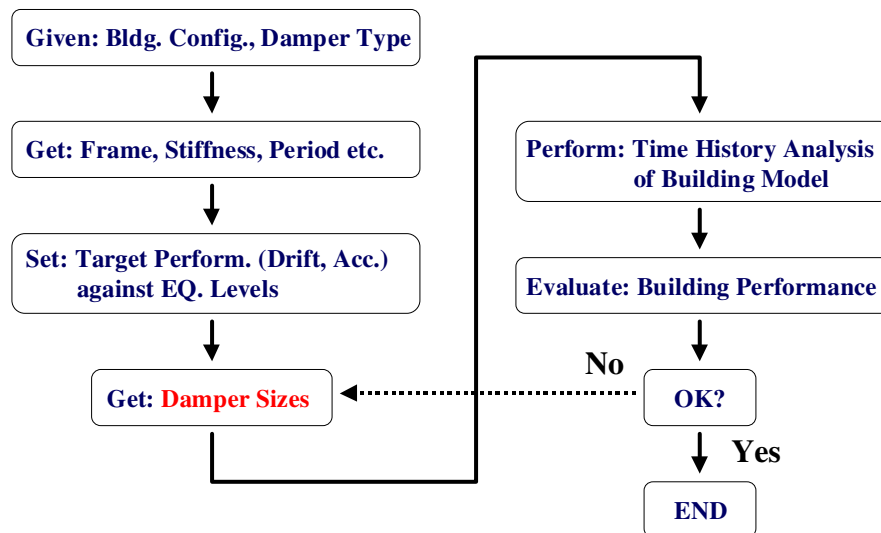


Figure 7 Summary of Damper and System Design Procedures

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., 1, 3, 4].

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. Figure 5 summarizes the design procedures. Numerous examples and details for the design procedures are documented in the JSSI manual [1].

### 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 (Figure 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 earlier [1, 28].

The element involving *viscous damper* uses, unlike the oil damper above, a nonlinear dashpot whose force is a fractional power of deformation rate [1, 26]. For some types possessing elastic stiffness, the model considers an in-series combination of the spring and the nonlinear dashpot [1, 27]. 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 [1, 6, 7], and another model directly expresses the constitutive equation of the damper using fractional time-derivatives of the force and deformation [1, 5, 11, 12, 25].

The element involving *steel damper* is proposed by utilizing the constitutive equations of steel material readily known from the past research [24], 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.

## 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 [1]. 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.

## ACKNOWLEDGEMENTS

The writer acknowledges support from Japan Ministry of Education, Culture, Sport, Science, and Technology (MEXT) for his research on various passive control systems. The writer also thanks the students at Kasai Laboratory, Tokyo Institute of Technology for their dedications to this research.

## REFERENCES

1. JSSI Manual (2003), Design and Construction Manual for Passively Controlled Buildings, Japan Society of Seismic Isolation (JSSI), First Edition, Tokyo, JAPAN, October (in Japanese, 405 pages).
2. JSCA Specifications (2000), Design Methodologies for Response Controlled Structures, Japan Structural Consultants Association (JSCA), Tokyo, JAPAN, December, 2000 (in Japanese, 445 pages).
3. Kasai, K., Fu, Y., and Watanabe, A. (1998), "Passive Control Systems for Seismic Damage Mitigation," Journal of Structural Engineering, American Society of Civil Engineers, 124(5), 501-512.
4. Fu, Y. and Kasai, K., (1998), "Comparative Study of Frames Using Viscoelastic and Viscous Dampers", J. Struct. Eng., American Society of Civil Engineers, 122 [10], pp. 513-522.
5. Kasai, K., Teramoto, M., Okuma, K., and Tokoro, K. (2001), "Constitutive Rule for Viscoelastic Materials Considering Temperature, Frequency, and Strain Sensitivities (Part 1: Linear Model with Temperature and Frequency Sensitivities)", Journal of Structural and Construction Engineering (Transactions of AIJ), No. 543, pp. 77-86, May. (in Japanese)
6. Kasai, K. and Okuma, K. (2001), "Kelvin-Type Formulation and Its Accuracy for Practical Modeling of Linear Viscoelastic Dampers (Part 1: One-Mass System Having Damper and Elastic / Inelastic Frame)", Journal of Structural and Construction Engineering (Transactions of AIJ), No. 550, pp. 71-78, Dec. (in Japanese)
7. Kasai, K. and Okuma, K. (2002), "Accuracy Enhancement of Kelvin-Type Modeling for Linear Viscoelastic Dampers (A Refined Model Including Effect of Input Frequency on Material Property)", Journal of Structural Engineering, Architectural Institute of Japan (AIJ), 48B, pp.545-553, March. (in Japanese)

8. Kasai, K., Teramoto, M., and Watanabe, Y. (2002), "Behavior of a Passive Control Damper Combining Visco-Elastic and Elasto-Plastic Devices in Series", *Journal of Structural and Construction Engineering (Transactions of AIJ)*, No. 556, pp. 51-58, June. (in Japanese)
9. Kasai, K. and Jodai, A. (2002), "Dynamic Property, Behavior, and Their Simplified Estimation Rules for a Passive Control System with Stud-Type Viscoelastic Damper", *Journal of Structural and Construction Engineering (Transactions of AIJ)*, No. 558, pp. 125-132, Aug. (in Japanese)
10. Kasai, K., Motoyui, S., and Ooki, Y. (2002), "Application of Viscoelastic Dampers to Space Frames and Response Prediction Methods for a Single-Directional Earthquake", *Journal of Structural and Construction Engineering (Transactions of AIJ)*, No. 561, pp. 125-135, Nov. (in Japanese)
11. Kasai, K. and Tokoro, K. (2002), "Constitutive Rule for Viscoelastic Materials Having Temperature, Frequency, and Strain Sensitivities (Part 2: Nonlinear Model Based on Temperature-Rise, Strain, and Strain-Rate)", *Journal of Structural and Construction Engineering (Transactions of AIJ)*, No. 561, pp. 55-63, Nov. (in Japanese)
12. Kasai, K., Ooki, Y., Amemiya, K., and Kimura, K. (2003), "A Constitutive Rule for Viscoelastic Materials Combining Iso-Butylene And Styrene Polymers (Part 1: Linear Model Considering Temperature And Frequency Sensitivities)", *Journal of Structural and Construction Engineering (Transactions of AIJ)*, No. 569, pp.47-54, July. (in Japanese)
13. Kasai, K., Ito, H., and Watanabe, A. (2003), "Peak Response Prediction Rule for a SDOF Elasto-Plastic System Based on Equivalent Linearization Technique", *Journal of Structural and Construction Engineering (Transactions of AIJ)*, No. 571, pp.53-62, Sep. (in Japanese)
14. Kasai, K., Suzuki, A., and Oohara, K. (2003), "Equivalent Linearization of a Passive Control System Having Viscous Dampers Dependent on Fractional Power of Velocity", *Journal of Structural and Construction Engineering (Transactions of AIJ)*, No. 574, pp.77-84, Dec. (in Japanese)
15. Kasai, K. and Okuma, K. (2004), "Evaluation Rule and Its Accuracy for Equivalent Period and Damping of Frequency-Dependent Passive Control Systems — Global Damping Model of One-Mass System Having Elastic Frame and Either Viscoelastic or Oil Damper —", *Journal of Structural and Construction Engineering (Transactions of AIJ)*, (in Review)
16. Ooki, Y., Kasai, K., and Takahashi, O. (2004), "Performance of Velocity-Dependent Dampers under Extremely Small Excitations", *Journal of Structural Engineering, Architectural Institute of Japan (AIJ)*, 50B, March (in Print). (in Japanese)
17. Kasai, K., Sakata, H., Komehana, S., and Miyashita, Y. (2004), "Experimental Study on Daynamic Behavior of Timber Frame with Viscoelastic Damper", *Journal of Structural Engineering, Architectural Institute of Japan (AIJ)*, 50B, March (in Print). (in Japanese)
18. Kasai, K. and Nishimura, T. (2004), "Equivalent Linearization of Passive Control System Having Oil Damper Bi-Linearly Dependent on Velocity", *Journal of Structural and Construction Engineering (Transactions of AIJ)*, (in Review). (in Japanese)
19. Kasai, K., Kibayashi M., Takeuchi T., Kimura Y., Saito Y., Nagashima I., Mori H., Uchikoshi M., Takahashi O., and Oohara K. (2002), "Principles and Current Status of Manual for Design and Construction of Passively-Controlled Buildings: Part-1: Background Scope, and Design Concept", *Proc. Structural Engineers World Congress (SEWC)*, Yokohama, JAPAN, CD-ROM, T2-2-a-1
20. Kibayashi, M., Kasai, K., Tsuji, Y., Kato, S., Kikuchi, M., Kimura, Y., and Kobayashi, T. (2002), "Principles and Current Status of Manual for Design and Construction of Passively-Controlled Buildings: Part-2 JSSI Criteria for Implementation of Energy Dissipation Devices", *Proc. Structural Engineers World Congress (SEWC)*, Yokohama, JAPAN, CD-ROM, T3-3-1
21. Takeuchi, T., Kasai, K., Ohara, K., Nakajima, H., and Kimura, Y. (2002), "Performance Evaluation and Design of Passively Controlled Buildings Using Equivalent Linearization", *Proc. Structural Engineers World Congress (SEWC)*, Yokohama, JAPAN, CD-ROM, T2-2-a-2
22. Ichikawa, Y., Takeuchi, T., Morimoto, S., and Sugiyama, M. (2002), "Practical Design of High-Rise Structure Using Viscoelastic Dampers and Hysteretic Dampers", *Proc. Structural Engineers World Congress (SEWC)*, Yokohama, JAPAN, CD-ROM, T2-2-a-3

23. Kanada, M., Kasai, K., and Okuma, K. (2002), "Innovative Passive Control Scheme: a Japanese 12-Story Building with stepping Columns and Viscoelastic Dampers", Proc. Structural Engineers World Congress (SEWC), Yokohama, JAPAN, CD-ROM, T2-2-a-5
24. Ono, Y., Kaneko, H., and Kasai, K. (2002), "Time-History Analysis Models for Steel Dampers", Proc. Structural Engineers World Congress (SEWC), Yokohama, JAPAN, CD-ROM, T2-2-b-1
25. Ooki, Y., Kasai, K., and Tokoro, K. (2002), "Time-History Analysis Models for Linear and Nonlinear Viscoelastic Dampers", Proc. Structural Engineers World Congress (SEWC), Yokohama, JAPAN, CD-ROM, T2-2-b-2
26. Oohara, K., and Kasai, K. (2002), "Time-History Analysis Models for Nonlinear Viscous Dampers", Proc. Structural Engineers World Congress (SEWC), Yokohama, JAPAN, CD-ROM, T2-2-b-3
27. Sekiguchi, Y., and Takahashi, O. (2002), "Time-History Analysis Models for Nonlinear Viscous Damping Wall", Proc. Structural Engineers World Congress (SEWC), Yokohama, JAPAN, CD-ROM, T2-2-b-4
28. Takahashi, O. and Sekiguchi, Y. (2002), "Time-History Analysis Models for Nonlinear Oil Dampers", Proc. Structural Engineers World Congress (SEWC), Yokohama, JAPAN, CD-ROM, T2-2-b-5
29. Tsuyuki, Y., Kamei, T., Gofuku, Y., Iiyama, F., and Kotake, Y. (2002), "Performance and Quality Control of Oil-Damper", Proc. Structural Engineers World Congress (SEWC) , Yokohama, JAPAN, CD-ROM, T3-3-2
30. Furukawa, Y., Kawaguchi, S., Sukagawa, M., Masaki, N., Sera, S., Kato, N., Washiyama, Y., and Mitsusaka, Y. (2002), "Performance and Quality Control of Viscous Dampers", Proc. Structural Engineers World Congress (SEWC), Yokohama, JAPAN, CD-ROM, T3-3-3
31. Okuma, K., Ishikawa, K., Oku, T., Sone, Y., Nakamura, H., and Masaki, N. (2002), "Performance and Quality Control of Viscoelastic Dampers", Proc. Structural Engineers World Congress (SEWC), Yokohama, JAPAN, CD-ROM, T3-3-4
32. Nakata, Y. (2002), "Performance and Quality Control of Steel Hysteretic Damper", Proc. Structural Engineers World Congress (SEWC), Yokohama, JAPAN, CD-ROM, T3-3-5