The 2013 World Congress on
Advances in Structural Engineering and Mechanics (ASEM13)
Jeju, Korea, September 8-12, 2013

Optimal placement of hysteretic dampers via adaptive smoothing algorithm

*Yu Murakami[1], Katsuya Noshi[1], Kohei Fujita[2],
Masaaki Tsuji[3] and Izuru Takewaki[4]

[1)-4)] *Department of Architecture and Architectural Engineering, Kyoto University*
Kyotodaigaku-Katsura, Nishikyo-ku, Kyoto 615-8540, Japan
[4)] takewaki@archi.kyoto-u.ac.jp

ABSTRACT

Since hysteretic dampers have nonlinear stiffness properties with sensitive plastic flow and input earthquake ground motions are random in time and frequency domains, the seismic response of a building with hysteretic dampers deviates greatly depending on the installed quantity of dampers. This characteristic could become a barrier to a reliable formulation of optimal damper placement. In order to overcome such difficulty, a new optimization method including a variable adaptive step length is proposed. The proposed method to solve the optimum design problem is a successive procedure which consists of two steps. The first step is a sensitivity analysis by using nonlinear time-history response analyses, and the second step is a modification of the set of damper quantities based upon the sensitivity analysis. Numerical examples are presented to demonstrate the effectiveness and validity of the proposed design method.

1) Graduate student
2) Assistant Professor
3) Associate Professor
4) Professor

1. INTRODUCTION

The concept of performance-based design plays a key role in the current structural design practice of buildings. In earthquake-prone countries, the philosophy of earthquake-resistant design to resist ground shaking with sufficient stiffness and strength of a building itself has also been accepted as a relevant structural design concept for many years. On the other hand, a new strategy based on the concept of active and passive structural control has been introduced rather recently in order to provide structural designers with powerful tools for performance-based design.

While active control has some issues to be resolved from the viewpoint of reliability during severe earthquake ground motions and cost, passive control is being widely used for building structures under earthquake ground motions (Soong and Dargush 1997, Hanson and Soong 2001, de Silva 2007, Takewaki 2009, Lagaros et al. 2012). Hysteretic steel dampers (shear deformation type, buckling restrained type), viscous wall-type dampers, viscous oil dampers, visco-elastic dampers, friction dampers, tuned mass dampers, inertial mass dampers (Takewaki et al. 2012) are representative ones. Recently viscous oil dampers (called oil dampers hereafter) are often used based on their stable mechanical properties, low frequency and temperature dependencies and cost effectiveness, etc. together with low cost hysteretic steel dampers. Compared to oil dampers, hysteretic steel dampers suit the strength-type performance check and are often preferred in the retrofit of buildings. It should be emphasized that, during the 2011 Tohoku (Japan) earthquake, the Osaka WTC building of 256(m) high was shaken so hard irrespective of its long distance (800km) from the epicenter (Takewaki et al. 2011). It is said that this results from the resonance of the building with the so-called long-period ground motion. To respond to this unfavorable situation, the retrofit of this building is under planning with oil dampers and hysteretic steel dampers. It should be remembered that the oil dampers and inertial mass dampers do not change the natural period of a building which may cause a resonance with the long-period ground motion stated above. On the other hand, the hysteretic steel dampers can change the natural period of a building by yielding even in the early vibration process.

Many research works have been accumulated so far on the damper optimization (Zhang and Soong 1992, Tsuji and Nakamura 1996, Takewaki 1997, 2000, Garcia 2001, Singh and Moreschi 2001, Uetani et al. 2003, Trombetti and Silvestri 2004, Liu et al. 2005, Lavan and Levy 2006, Silvestri and Trombetti 2007, Aydin et al. 2007, Cimellaro 2007, Attard 2007, Lavan and Dargush 2009, Lagaros et al. 2012, Hwang et al. 2013). While most of them deal with linear responses, quite a few treat non-linear responses in building structures or dampers (Uetani et al. 2003, Attard 2007, Lavan and Levy 2005, 2010, Whittle et al. 2012, Lagaros et al. 2012, Adachi et al. 2013). However, there is no research on the optimization of location and quantity of dampers which deals with non-linear responses and includes simple and systematic algorithms.

The purpose of this paper is to propose a new optimization method including a variable adaptive step length for shear buildings with hysteretic dampers subjected to a set of design earthquake ground motions under the constraint on the total cost. The response sensitivity of buildings including hysteretic dampers is high and a devised algorithm of adaptive step-length is useful to obtain a smooth and reliable response sensitivity. The high response sensitivity of buildings including hysteretic dampers may result from the timing of fast plastic flow and random process of input and the change of the natural period of a building depending on the installed quantity of hysteretic dampers. The proposed procedure enables structural designers to derive a series of optimal distribution of damper quantities with respect to the level of the total cost of dampers which is useful in seeking for the relation between the optimal response level and the quantity and placement of passive dampers. Numerical examples reveal some features of the optimal distribution of various passive dampers.

2. OPTIMAL HYSTERETIC DAMPER PLACEMENT PROBLEM

Consider an *N*-story shear building model with hysteretic steel dampers as shown in Fig.1. A stiffness proportional viscous damping is employed here in the main frame (damping ratio=0.02).

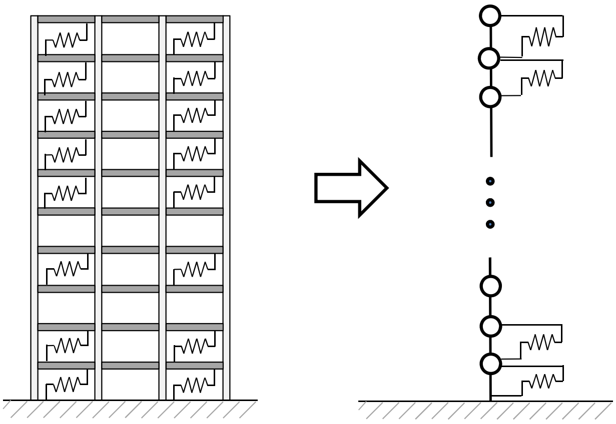


Fig.1 *N*-story planar frame with hysteretic steel dampers and its modeling into shear building model with hysteretic steel dampers

2.1 Modeling of hysteretic dampers

Steel hysteretic dampers are used in this paper. The initial stiffness k_{dj} and the yield displacement u_y are the major parameters to characterize the present steel hysteretic dampers. An elastic-perfectly plastic restoring force characteristic as shown in Fig.2 is assumed.

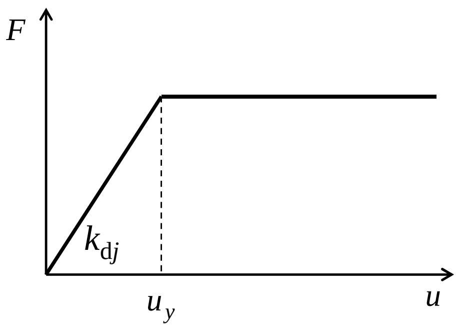


Fig.2 Force-deformation relation of hysteretic damper

2.2 Design earthquake ground motions and envelope response

Two representative recorded ground motions, i.e. El Centro NS 1940 (maximum velocity=0.5m/s) and Hachinohe NS 1968 (maximum velocity=0.5m/s), are employed as the design earthquake ground motions. The envelope response of the maximum interstory drift for multiple candidate ground motions as shown in Fig.3 is used in this paper. Although an example for two ground motions is presented here, this is applicable to a more general case for multiple ground motions.

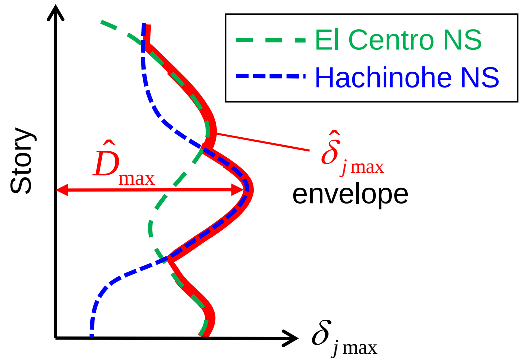


Fig.3 Envelope response

2.3 Optimal damper placement problem

The design problem of hysteretic dampers may be stated as follows.

[Problem] Find $\mathbf{k}_{\mathrm{d}} = \{k_{\mathrm{d}j}\}$ so as to minimize F subject to

$$\sum_{j=1}^{N} k_{\mathrm{d}j} = \bar{C}_{\mathrm{d}} \tag{2}$$

In this problem, $\bar{C}_{\mathrm{d}}$ is the specified sum of stiffnesses of hysteretic dampers. $\hat{D}_{\max}$ is employed as F. For simplicity of expression, $\hat{D}_{\max}$ is expressed simply as $D_{\max}$ later.

Since hysteretic dampers have nonlinear stiffness properties with sudden, large stiffness change and input earthquake ground motions are random, the seismic response of a building with hysteretic dampers deviates greatly depending on the installed quantity of dampers. The timing of fast plastic flow and random process of input may be the main reason of the response randomness. This characteristic disturbs a reliable formulation of the optimal damper placement. Fig.4 shows the variation of the maximum interstory drift with respect to the sum of hysteretic damper stiffnesses. The initial design of the hysteretic damper stiffness is proportional to the main frame stiffness and the stiffness ratio to the main frame is 5. In Fig.4, the hysteretic damper stiffnesses have been changed so that the hysteretic damper stiffness is proportional to the main frame stiffness.

In order to overcome such difficulty, a new optimization method including a variable adaptive step length for smoothing is proposed. Although a constraint on accumulated plastic deformation ratio is sometimes required in hysteretic dampers for long-duration earthquake ground motions (AIJ 2011, 2012, Takewaki et al. 2011, Celebi et al. 2012), this is not taken into account here because of a simple, essential presentation of a new optimization procedure.

Fig.5 shows the maximum interstory drift and the variation of the maximum interstory drift to the change (decrease) of damper stiffness in the story marked by circle. It can be observed that it is difficult to predict the variation of the maximum interstory drifts from the story number with the stiffness change.

Fig.6 illustrates the maximum interstory drift with respect to step number. It can also be confirmed that the seismic response of a building with hysteretic dampers deviates greatly depending on the installed quantity of dampers.

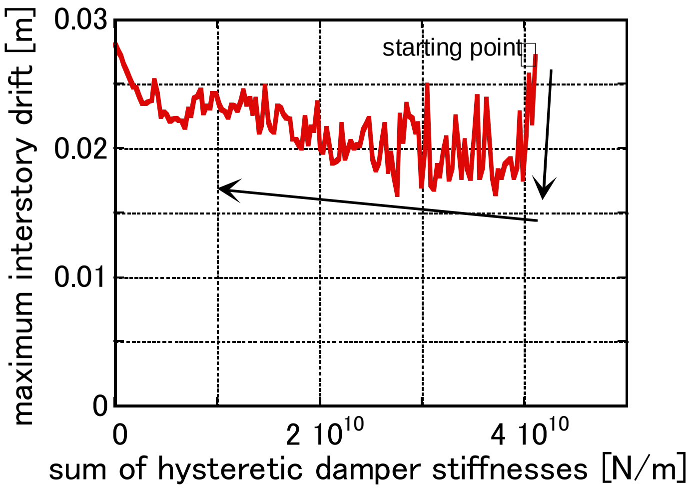


Fig.4 Maximum interstory drift with respect to sum of hysteretic damper stiffness

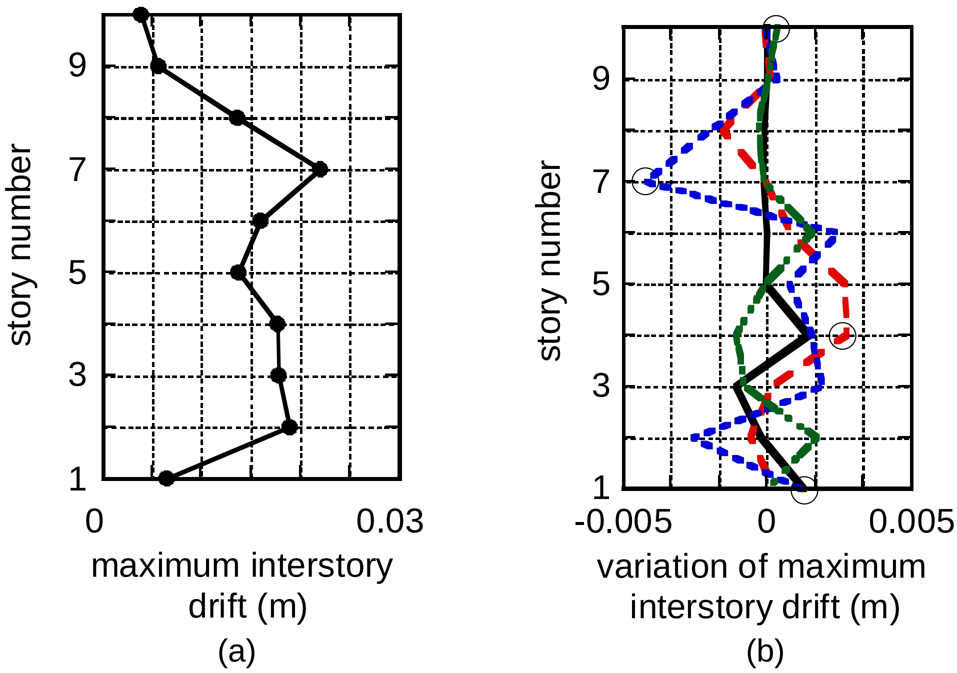


Fig.5 Maximum interstory drift and variation of maximum interstory drift to change (decrease) of damper stiffness in story marked by circle

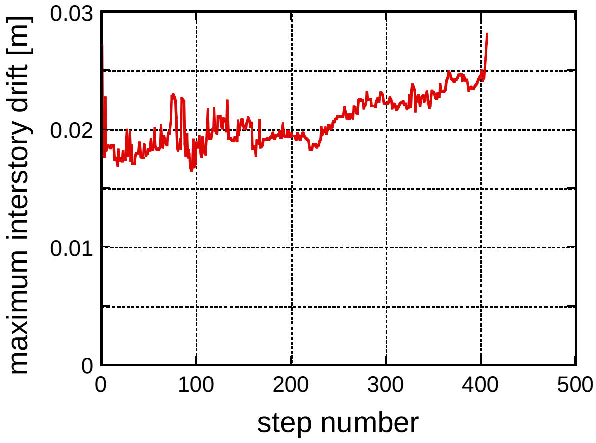


Fig.6 Maximum interstory drift with respect to step number

2.4 Optimization algorithm including variable adaptive step length

Fig.7 shows a schematic diagram of the proposed sensitivity evaluation algorithm including variable adaptive step length. Among several candidates of the decreased hysteretic damper cost, the decreased hysteretic damper cost attaining the lowest value of the maximum interstory drift is employed as the next-step sensitivity. Fig.8 presents the flowchart of hysteretic damper optimization-1. Although the minimum value is used in this example, the maximum value of the maximum interstory drift can be employed alternatively in consideration of the safety level of the passively controlled buildings. An example using this maximum value of the maximum interstory drift will be shown later. The average value of the maximum interstory drift may be another possibility.

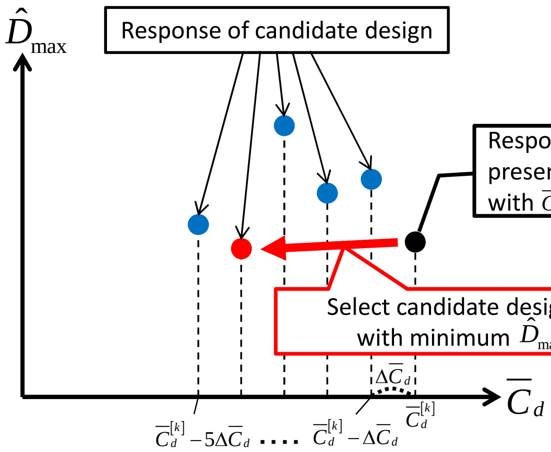


Fig.7 Sensitivity evaluation algorithm including variable adaptive step length-1
(Selection of candidate design with minimum of maximum interstory drift)

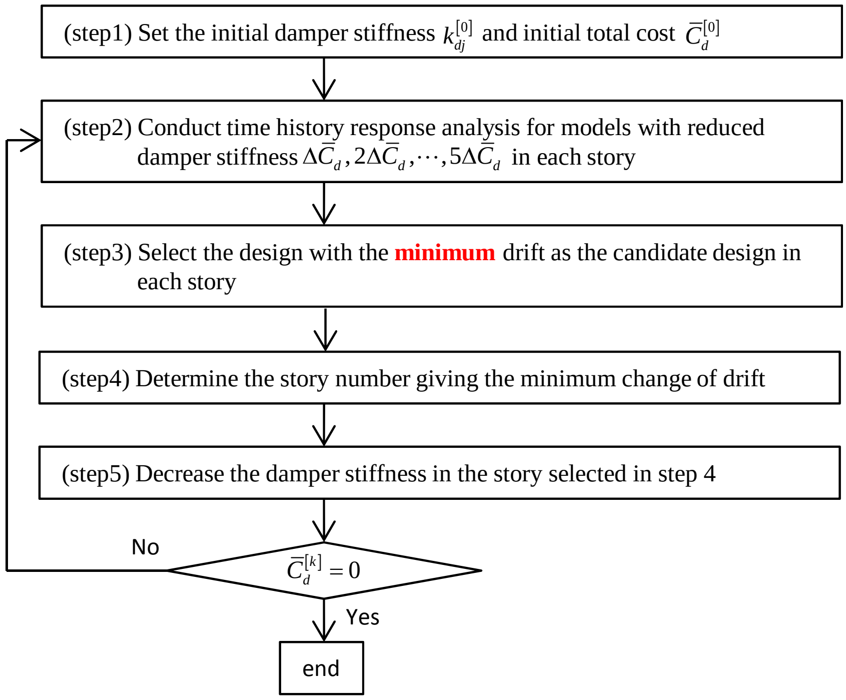


Fig.8 Flowchart of hysteretic damper optimization-1

A practical procedure for optimal oil damper design without laborious mathematical programming techniques has been proposed for reducing the computational load (Adachi et al. 2013). There are two practical aspects: (1) use of a reduced model (static condensation) from a frame model for computational efficiency, (2) search of a series of optimal damper distribution for different total damper quantities. Although a shear building model is used here, the reduced model (static condensation) developed by Adachi et al. (2013) can be used if desired. Fig.9 illustrates the conceptual approximate solution procedure. The design algorithm may be summarized as follows:

[Step 1] The along-height sum of hysteretic damper stiffnesses is determined (as the stiffness ratio to the main frame stiffness).

[Step 2] Produce $N \times 5$ candidates in which damper stiffnessses $\Delta C_\mathrm{d}, 2\Delta C_\mathrm{d}$, $3\Delta C_\mathrm{d}$, $4\Delta C_\mathrm{d}, 5\Delta C_\mathrm{d}$ are reduced from the present hysteretic damper stiffness in each story. Compute the objective function for each model constructed in Step 2 through nonlinear time-history response analysis.

[Step 3] Select the design with the minimum drift as the candidate design in each story.

[Step 4] Select the best candidate with the minimum objective function (drift change) from the candidates produced in Step 3.

[Step 5] Decrease the damper stiffness in the story selected in step 4. Then go to Step 2.

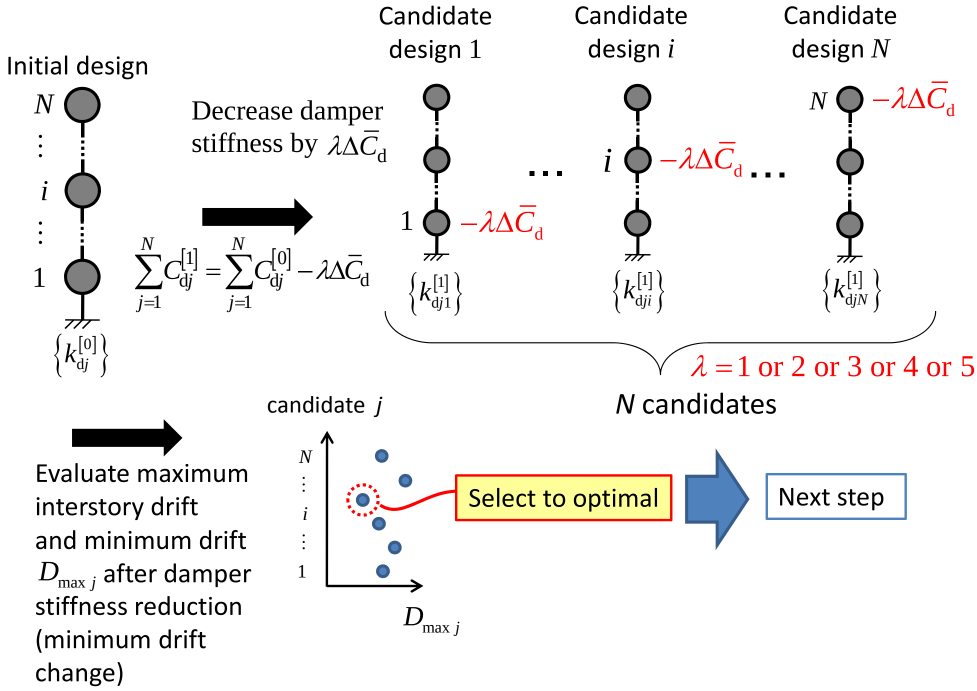


Fig.9 Conceptual diagram of hysteretic damper optimization

3. NUMERICAL EXAMPLES

The main structure has been designed so that it has a fundamental natural period of 1.05(s) and a realistic stiffness distribution (see Appendix 1). The constant mass is 1.0×10^6 kg and the structural damping ratio is 0.02. The yield displacement of hysteretic dampers is 0.005m and the stiffness ratio of hysteretic dampers to the main frame stiffness in the initial design is 5.

3.1 Example 1 (Employment of *minimum* value of maximum interstory drift in algorithm of variable adaptive step length)

An example using the algorithm explained in Section 2.4 is presented here. Fig.10 shows the plot of the maximum interstory drift with respect to the sum of hysteretic damper stiffnesses. The sum of hysteretic damper stiffnesses is decreased gradually. Fig.10 indicates clearly the effect of upper limit of damper variation. Fig.11(a) illustrates the distribution of hysteretic damper stiffnesses and Fig.11(b) shows the distributions of the maximum interstory drifts. It can be understood from Fig.11(a) that the first-story damper is reduced fast in the increasing step. This may result from the fact that the interstory drift in the first story is smaller compared to other stories and the installation of hysteretic dampers in the first story is not effective in this example. It can also be observed from Fig.11(b) that the maximum ductility factor of hysteretic dampers is about 4-5 in later steps.

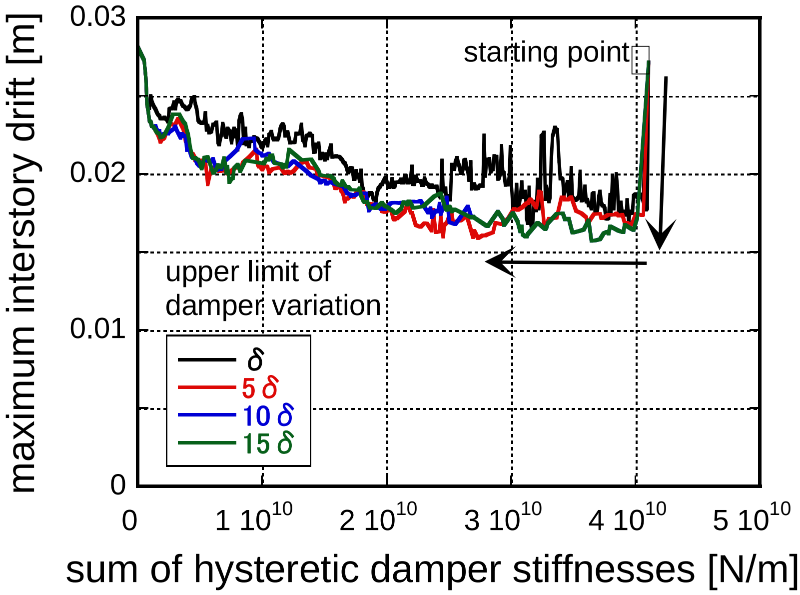
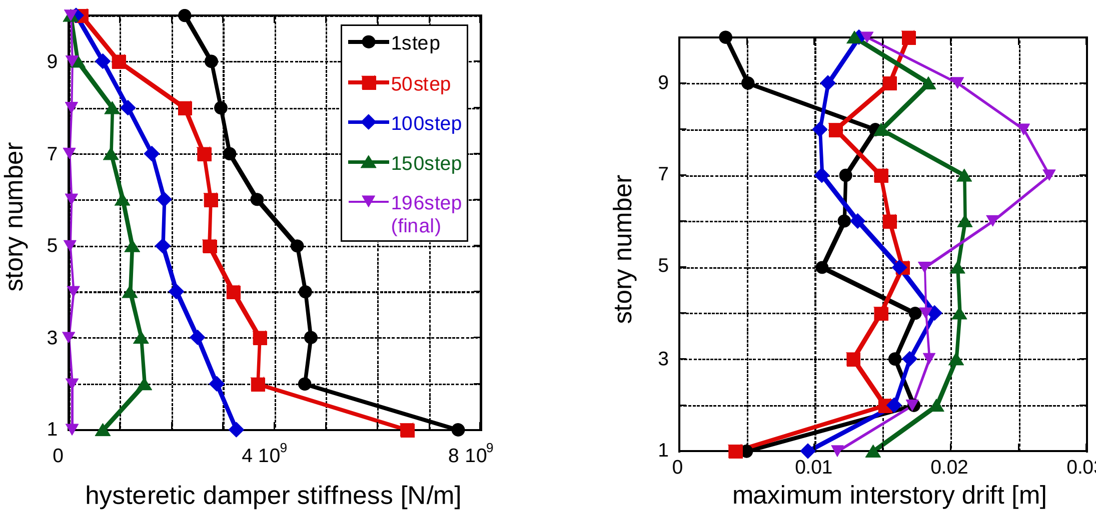


Fig.10 Effect of upper limit of damper variation on damper optimization



(a)Distribution of hysteretic damper stiffness (b)Maximum interstory drift

Fig.11 Optimal design (Example 1: Minimum drift-sensitivity criterion)

3.2 Example 2 (Employment of *maximum* value of maximum interstory drift in algorithm of variable adaptive step length)

In place of the algorithm in Section 2.4, another one is employed here, i.e. the selection of the design with the **maximum** drift as the candidate design in each story in Step 3. Fig.12 presents the sensitivity evaluation algorithm including variable adaptive step length (Selection of candidate design with maximum of maximum interstory drift). Fig.13 illustrates the flowchart of hysteretic damper optimization-2.

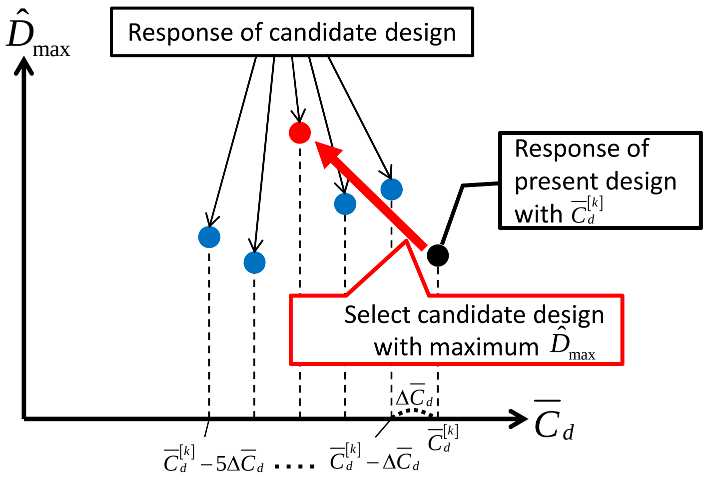


Fig.12 Sensitivity evaluation algorithm including variable adaptive step length-2 (Selection of candidate design with maximum of maximum interstory drift)

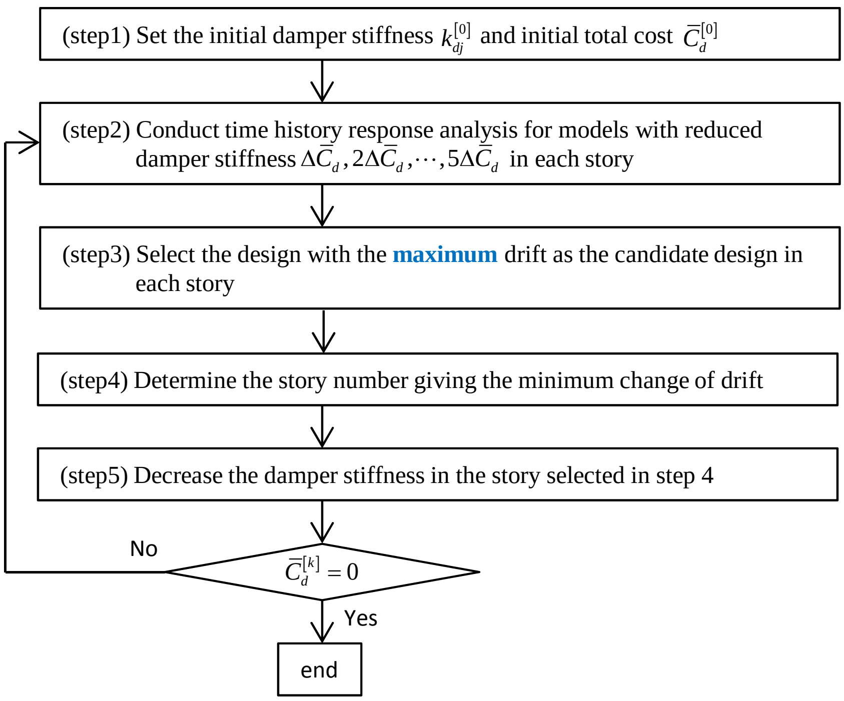


Fig.13 Flowchart of hysteretic damper optimization-2

Fig.14 shows the plot of the maximum interstory drift with respect to the sum of hysteretic damper stiffnesses. The sum of hysteretic damper stiffnesses is decreased gradually. The plot for δ is the same as that for δ in Fig.10 because the minimization or maximization procedure is not applied to the case for δ (only one case for δ). Fig.14 indicates clearly the effect of upper limit of damper variation, i.e. smoothing of variation. Fig.15(a) illustrates the distribution of hysteretic damper stiffnesses and Fig.15(b) shows the distributions of the maximum interstory drifts. It can be observed from Fig.15(a) that the maximum interstory drift distributions of the models obtained in this new algorithm are not different so much from those in Fig.11(a). Although Fig.15(b) is also similar to Fig.11(b), a slight change can be observed in upper stories.

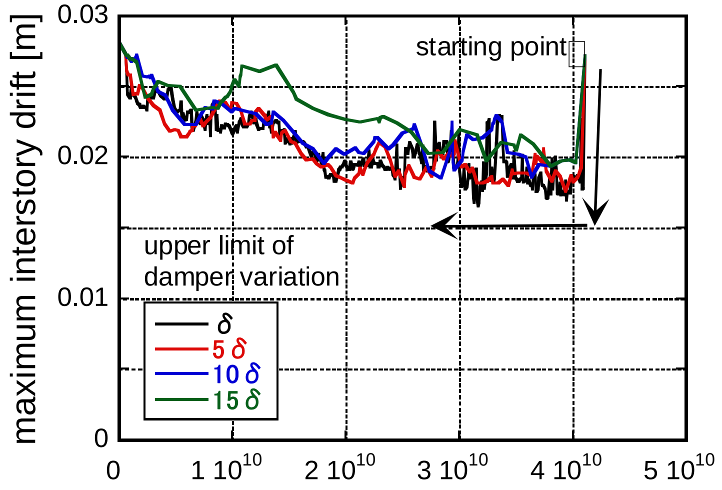
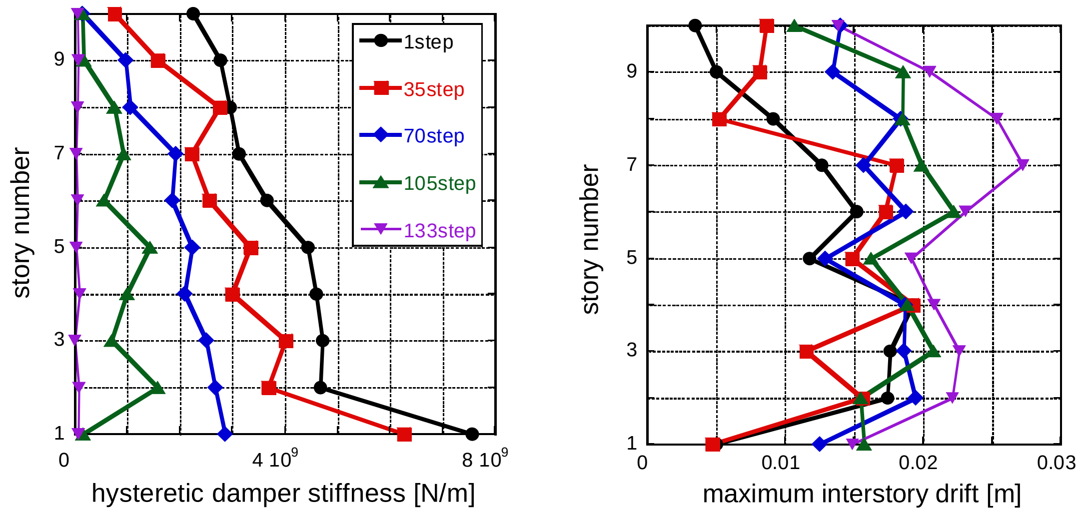


Fig.14 Effect of upper limit of damper variation on damper optimization



(a)Distribution of hysteretic damper stiffness (b)Maximum interstory drift

Fig.15 Optimal design (Example 2: Maximum drift-sensitivity criterion)

4. CONCLUSIONS

The following conclusions have been derived.

(1) The proposed method for optimal placement of hysteretic dampers takes full advantage of a sensitivity-based redesign algorithm including nonlinear response analysis in the optimization process. The method enables structural designers to find an optimal passive damper in each design step. The method is general and applicable to any type of passive dampers.

(2) The response sensitivity of buildings including hysteretic dampers is high and a devised algorithm of adaptive step-length is useful to obtain a smooth and reliable response sensitivity.

(3) Employment of the *minimum or maximum* value of the maximum interstory drift can be used in the algorithm of variable adaptive step length. Both algorithms provide similar results on the optimal damper placement.

ACKNOWLEDGEMENTS

Part of the present work is supported by the Grant-in-Aid for Scientific Research of Japan Society for the Promotion of Science (No.24246095). This support is greatly appreciated.

REFERENCES

Adachi, F., Yoshitomi, S., Tsuji, M. and Takewaki, I. (2013). Nonlinear optimal oil damper design in seismically controlled multi-story building frame, *Soil Dynamics and Earthquake Engineering*, 44(1), 1-13.

Architectural Institute of Japan (AIJ) (2011). *Preliminary reconnaissance report of the 2011 Tohoku-Chiho Taiheiyo-Oki, earthquake*, July 2011 [in Japanese].

Architectural Institute of Japan (AIJ) (2012). *Preliminary reconnaissance report of the 2011 Tohoku-Chiho Taiheiyo-Oki, earthquake*, Springer.

Attard TL. (2007). Controlling all interstory displacements in highly nonlinear steel buildings using optimal viscous damping. *J Struct Engrg*, ASCE; 133(9): 1331-1340.

Aydin E, Boduroglub MH and Guney D. (2007). Optimal damper distribution for seismic rehabilitation of planar building structures. *Engineering Structures*; 29: 176–185.

Celebi, M., Okawa, I., Kashima, T., Koyama, S., and Iiba, M. (2012), Response of a tall building far from the epicenter of the 11 March 2011 M9.0 Great East Japan earthquake and aftershocks, *Struct. Design Tall Spec. Build.* (published online in 2012).

Cimellaro GP. (2007). Simultaneous stiffness-damping optimization of structures with respect to acceleration, displacement and base shear. *Engineering Structures*; 29: 2853-2870.

de Silva CW (ed.) (2007). *Vibration damping, control, and design*. CRC Press.

Garcia DL. (2001). A simple method for the design of optimal damper configurations in MDOF structures. *Earthquake Spectra*; 17: 387-398.

Hanson RD and Soong TT. (2001). *Seismic design with supplemental energy dissipation devices*. EERI, Oakland, CA.

Hwang, J.S., Lin, W.C. and Wu, N.J. (2013). Comparison of distribution methods for viscous damping coefficients to buildings, *Structure and Infrastructure Engineering*, 9(1), 28-41.

Lagaros, ND, Plevris, V. and Mitropoulou, CC. (Editors) (2012). *Design optimization of active and passive structural control systems*, IGI Global.

Lavan O, Dargush GF (2009). Multi-Objective Evolutionary Seismic Design with Passive Energy Dissipation Systems, *J Earthquake Engineering*, 13(6), 758-790.

Lavan O and Levy R. (2005). Optimal design of supplemental viscous dampers for irregular shear-frames in the presence of yielding. *Earthq Engrg Struct Dyn*; 34(8): 889-907.

Lavan O and Levy R. (2006). Optimal design of supplemental viscous dampers for linear framed structures. *Earthq Engrg Struct Dyn*; 35: 337-356**.**

Lavan O. and Levy R. (2010). Performance based optimal seismic retrofitting of yielding plane frames using added viscous damping, *Earthquakes and Structures*, 1(3), 307-326.

Liu W, Tong M and Lee G. (2005). Optimization methodology for damper configuration based on building performance indices. *J Struct Engrg*, ASCE; 131(11): 1746-1756.

Noshi, K., Yoshitomi, S., Tsuji, M. and Takewaki, I. (2013). Optimal nonlinear oil damper design in seismically controlled multi-story buildings for relief forces and damping coefficients, *J. Structural Engineering*, Architectural Institute of Japan, Vol.59B (in Japanese).

Silvestri S and Trombetti T. (2007). Physical and numerical approaches for the optimal insertion of seismic viscous dampers in shear-type structures, *J Earthquake Engineering*; 11: 787-828.

Singh MP and Moreschi LM. (2001). Optimal seismic response control with dampers. *Earthq Engrg Struct Dyn* 2001; 30: 553-572.

Soong TT and Dargush GF. (1997). *Passive energy dissipation systems in structural engineering*. John Wiley & Sons, Chichester.

Takewaki I. (1997). Optimal damper placement for minimum transfer functions. *Earthq Engrg Struct Dyn*; 26: 1113-1124.

Takewaki I. (2009). *Building control with passive dampers: -Optimal performance-based design for earthquakes-.* John Wiley & Sons Ltd. (Asia).

Takewaki I. (2000). Optimal Damper placement for planar building frames using transfer functions, *Structural and Multidisciplinary Optimization*; 20(4): 280-287.

Takewaki I, Murakami S, Fujita K, Yoshitomi S and Tsuji M. (2011). The 2011 off the Pacific coast of Tohoku earthquake and response of high-rise buildings under long-period ground motions. *Soil Dynamics and Earthquake Engineering*; 31(11): 1511-1528.

Takewaki, I., Murakami, S., Yoshitomi, S. and Tsuji, M. (2012). Fundamental mechanism of earthquake response reduction in building structures with inertial dampers, *Structural Control and Health Monitoring*, 19(6), 590-608.

Takewaki I and Yoshitomi S. (1998). Effects of support stiffnesses on optimal damper placement for a planar building frame. *J. of The Structural Design of Tall Buildings*; 7(4): 323-336.

Trombetti T and Silvestri S (2004). Added viscous dampers in shear-type structures: The effectiveness of mass proportional damping, *Journal of Earthquake Engineering*, 8(2), 275-313.

Tsuji M and Nakamura T. (1996). Optimum viscous dampers for stiffness design of shear buildings. *J Structural Design of Tall Buildings*; 5: 217-234.

Tsuji M, Tanaka H, Yoshitomi S and Takewaki I. (2011). Model reduction method for buildings with viscous dampers under earthquake loading. *J Struct Construction Eng*, Architectural Institute of Japan; 76(665): 1281-1290 (in Japanese).

Uetani K, Tsuji M and Takewaki I. (2003). Application of optimum design method to practical building frames with viscous dampers and hysteretic dampers. *Engineering Structures*; 25: 579-592.

Whittle, J.K. , Williams, M.S., Karavasilis, T.L., Blakeborough (2012). A, A comparison of viscous damper placement methods for improving seismic building design, *J. Earthquake Engineering*, 16(4), 540-560.

Zhang RH and Soong TT. (1992). Seismic design of viscoelastic dampers for structural applications. *J Struct Engrg*, ASCE; 118: 1375-1392.

APPENDIX 1: Story stiffness of 10-story main frame

A 10-story main frame has been modeled into a 10-story shear building model. The 10-story shear building model is designed so that it possesses a fundamental natural period of 1.05(s) and a realistic stiffness distribution as shown below. The constant floor mass is 1.0×10^{6} kg which corresponds approximately to 30m$\times$30m floor plan. The structural damping ratio (stiffness-proportional viscous damping) is 0.02.

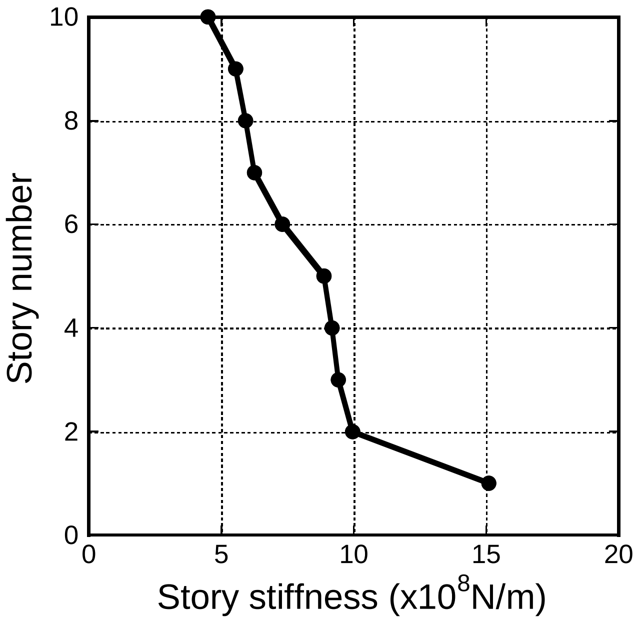


Fig.A1 Story stiffness of main frame