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OPTIMUM DESIGN METHOD FOR HIGH-RISE BUILDING FRAME WITH VISCOUS DAMPERS

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SUMMARY

Proposed is an optimum design method for a building frame with viscous dampers. The method consists of two steps. In the first step, a shear building model with viscous dampers is used and story stiffnesses are determined so that the designed shear building would exhibit specified distribution of interstory drifts under design spectrum-compatible earthquakes. In the second step, an optimum set of cross-sectional areas of a frame model is determined subject to constraints on interstory drifts and member-end strains under a set of design horizontal loads. The design loads and the damper damping coefficients of the shear building model are determined such that the designed shear building model and the designed frame model would have equivalent dynamic characteristics. Effect of overturning deformation on damper performance can be taken into consideration by repeating the two-step design procedure. Four design examples are presented to show efficiency and validity of the proposed design method. Time history analyses to artificial earthquake motions are performed to show accuracy of the proposed design method.

INTRODUCTION

Various types of viscous dampers have been used for over thirty years in many high-rise buildings in order to reduce or control wind-induced response and seismic response [Mahmoodi, 1969; Soong and Dargush, 1997]. Although there is a great number of experimental and theoretical studies about viscous dampers and buildings with the devices, most of them are concerned with characteristics of dynamic behavior of the devices [for example, Lee and Tsai, 1994; Tsai, 1994] and of the buildings with viscous dampers [for example, Scholl, 1984; Arima et al., 1988; Lin et al., 1991; Niwa et al., 1995].

There seem to be few papers concerning a problem of an optimum design of viscous dampers and buildings with the devices. Constantinou and Tadjbakhsh (1983) derived by parametric analysis an optimum damping coefficient of a damper placed on the first story of a shear building subjected to horizontal random earthquake motions such that the maximum response of the top story relative to the ground is minimized. Zhang and Soong (1992) proposed a seismic design method to find an optimal configuration of viscous dampers for a building with specified story stiffnesses. Hahn and Sathiavageeswaran (1992) made several parametric studies on the effects of damper distribution on the earthquake response of shear buildings, and showed for a building with uniform story stiffnesses that the dampers added to the lower half floors of the building reduce the earthquake response more effectively than the dampers added to the odd floors. While some other studies concerning an optimum design of viscous dampers are presented [for example, De Silva, 1981; Inaudi and Kelly, 1993; Takewaki, 1997] most of these studies have dealt with an optimum design of dampers attached to a structure with prescribed stiffnesses. Although viscous dampers reduce some overall response of the structure, a concentrated configuration of dampers due to optimization may cause an undesirable distribution of maximum responses if the stiffness distribution would not be modified appropriately corresponding to the damping coefficient distribution. No effective method, however, appears to have been presented for finding an optimum set of stiffnesses of a frame together with an optimum set of damping devices under behavioral constraints. Although Tsuji and

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Nakamura (1996) proposed an algorithm to find both the optimum story stiffness distribution and the optimum damper distribution for a shear building model and the algorithm is quite efficient for shear building models, this algorithm may not be practical for building frames with large degrees-of-freedom.

The purpose of this paper is to propose an optimum design method for a building frame with viscous dampers. The method consists of two steps. In the first step, a shear building model with viscous dampers is used and story stiffnesses are determined via inverse problem formulation [Nakamura and Tsuji, 1996] so that the designed shear building would exhibit specified distribution of interstory drifts under design spectrum-compatible earthquakes. Damping coefficients of the dampers of the shear building model are determined so that the coefficients coincide with the prescribed values of the frame model with respect to story shear deformations. In the second step, an optimum set of cross-sectional areas of the frame model is determined subject to constraints on interstory drifts and member-end strains under a set of design horizontal loads. The design loads are determined such that the designed shear building model and the designed frame model would have equivalent dynamic characteristics, i.e., stiffness and damping. This transformation from a shear building model to a frame model is based on the fact [Nakamura et al., 1990] that if the restoring force characteristics in the story level are equivalent between the frame model and its reduced shear building model, the maximum responses of both models seem to be almost equivalent under earthquake motions. Effect of overturning deformation on damper performance can be taken into consideration by repeating the two-step design procedure. Four design examples are presented to show efficiency and validity of the proposed design method. Time history analyses to artificial earthquake motions are performed to show accuracy of the proposed design method.

FRAME MODEL WITH VISCOUS DAMPERS

Consider a plane frame as a simplified model of 3-dimesional large building frames. Viscous dampers are assumed to be installed between neighboring floors by braces with sufficient stiffness as shown in Fig. 1. Damping coefficients of the dampers are assumed to be prescribed. Design earthquakes are defined by a set of earthquake motions compatible with a design displacement spectrum. Beams and columns are assumed to remain elastic under design moderate earthquakes.

A structure with viscous dampers exhibits strong non-proportional damping characteristics. Mean peak responses to the design earthquakes can be evaluated by some response spectrum methods such as extended CQC method [Igusa et al., 1984], in which effect of non-proportional damping is taken into consideration.

DEFINITION OF SHEAR MODEL

A shear building with viscous dampers is adopted as a reduced model of the frame model. The damping coefficient in each story of the shear building model is assumed to be expressed as a sum of a structural damping coefficient and a damper damping coefficient of the corresponding story. The latter is determined such that the coefficient is identical with total value of the damping coefficients in the corresponding story of the frame model with respect to story shear deformation.

TWO-STEP OPTIMUM DESIGN METHOD FOR FRAME WITH VISCOUS DAMPERS

Let N_M and N_F denote the number of members and the number of stories of the frame model, respectively, and let N_{Dj} denote the number of dampers in the *j*th story. Cross-sectional areas are treated as continuous design variables and are denoted by the set $\{A_i\}$. Consider an Optimum Design problem for a Building Frame with viscous dampers subjected to design earthquakes as follows:

Problem ODBF: Find a set of cross-sectional areas of the frame to minimize the following object function

$$f = \sum_{i=1}^{N_M} A_i \ell_i \tag{1}$$

subject to

$$\delta_{j\,max} \le \overline{\delta}_j \quad (j = 1,...,N_F) \quad , \quad \varepsilon_{i\,max} \le \overline{\varepsilon}_i \quad , \quad \overline{A}_i^L \le A_i \le \overline{A}_i^U \quad (i = 1,...,N_M) \tag{2a-c}$$

where A_i , ℓ_i, $\delta_{j\,max}$, and $\varepsilon_{i\,max}$ denote the cross-sectional area of the *i*th member, the length of the *i*th member, the maximum interstory drift of the *j*th story, and the maximum member-end strain of the *i*th member, respectively, and $\overline{\delta}_j$, $\overline{\varepsilon}_i$, $\overline{A}_i^L$, and $\overline{A}_i^U$ denote the upper bound of interstory drifts, the upper bound of member-end strains, and the lower bound and the upper bound of cross-sectional areas.

Problem ODBF may be solved by conventional optimum design algorithms. However, such a method seems to be not practical for a complicated building frame with many degrees-of-freedom subject to maximum response constraints (2a,b) under dynamic excitations, because evaluation of dynamic response, even if a response spectrum method is used, needs laborious computational tasks compared with that of static response.

On the other hand, optimum design method for frames subject to response constraints under static loads and response-constrained design method for reduced model, e.g., shear buildings, subject to response constraints under dynamic excitations may both be reasonably solved by powerful personal computers. On these basis, the following optimum design method incorporating the equivalent assumption between the frame model and its reduced model is proposed here:

Step 1. Compute initial damping coefficients $\left\{\tilde{c}_j^{(0)}\right\}$ of the shear building model by

$$\tilde{c}_j^{(0)} = \sum_{i=1}^{N_{Dj}} c_{ij} \cos^2\theta_{ij} \quad (j = 1,...,N_F) \tag{3}$$

where c_{ij} and θ_{ij} denote the prescribed damping coefficient of the *i*th damper in the *j*th story of the frame model and the angle of the damper from horizontal line, respectively. Equation (3) means that the effect of overturning deformation on damper performance is assumed to be neglected in initial design of shear building model. Next, compute story stiffnesses $\left\{k_j^{(0)}\right\}$ of the shear building model with damper damping coefficients $\left\{\tilde{c}_j^{(0)}\right\}$ so that the constraints

$$\delta_{j\,max} = \overline{\delta}_j \quad (j = 1,...,N_F) \tag{4}$$

would be satisfied [Nakamura and Tsuji, 1996], and determine initial design horizontal loads $\left\{H_j^{(0)}\right\}$ for optimum design of the frame model by

$$H_j^{(0)} = k_j^{(0)}\overline{\delta}_j - k_{j+1}^{(0)}\overline{\delta}_{j+1} \quad (j = 1,...,N_F - 1) \quad , \quad H_{N_F}^{(0)} = k_{N_F}^{(0)}\overline{\delta}_{N_F} \tag{5}$$

Step 2. Find a set of member cross-sectional areas $\left\{A_i^{(0)}\right\}$ under design loads $\left\{H_j^{(0)}\right\}$ subject to constraints (2a-c) by optimum design procedure [for example, Tsuji et al., 1999]. Next, evaluate maximum responses of the designed frame under design earthquakes by response spectrum method, such as extended CQC method. Furthermore, compute a set of ratios $\left\{R_{SDj}\right\}$ of story shear deformations to corresponding interstory drifts by

$$R_{SD1} = 1 \quad , \quad R_{SDj} = 1 - \Theta_{j-1} h_j / \delta_j \quad (j = 2,...,N_F) \tag{6}$$

where δ_j, h_j, and Θ_j denote the *j*th interstory drift to the design loads, the height of the *j*th story, and the rotational angle of the *j*th equivalent floor as shown in Fig. 1. If the maximum responses satisfy the constraints (2a) within good accuracy, the design method may be terminated. If not, re-compute damping coefficients $\left\{\tilde{c}_j^{(1)}\right\}$ of the shear building model by

$$\tilde{c}_j^{(1)} = \sum_{i=1}^{N_{Dj}} R_{SDj} c_{ij} \cos^2\theta_{ij} \quad (j = 1,...,N_F) \tag{7}$$

and repeat the procedure *Step* 1 to *Step* 2 for damper damping coefficients $\left\{\tilde{c}_j^{(1)}\right\}$ until the constraints (2a) are satisfied within good accuracy.

NUMERICAL EXAMPLES

Design Conditions

Let ω and h denote a eigenfrequency and a modal damping ratio, respectively. The following displacement response spectrum [Newmark and Hall, 1982] is used here for the design moderate earthquake:

$$S_D(\omega;h)=\begin{cases} S_D^A(\omega;h)=\ddot{u}_{g\,max}\{3.21-0.68\,ln(100h)\}\omega^{-2} & (\omega_U\le\omega) \\ S_D^V(\omega;h)=\dot{u}_{g\,max}\{2.31-0.41\,ln(100h)\}\omega^{-1} & (\omega_L\le\omega\le\omega_U) \\ S_D^D(\omega;h)=u_{g\,max}\{1.82-0.27\,ln(100h)\} & (\omega\le\omega_L) \end{cases} \tag{8a-c}$$

where $\ddot{u}_{g\,max}$, $\dot{u}_{g\,max}$, and $u_{g\,max}$ denote the maximum ground acceleration, the maximum ground velocity and the maximum ground displacement, respectively, and $\ddot{u}_{g\,max}=201(\mathrm{cm/s^2})$, $\dot{u}_{g\,max}=25(\mathrm{cm/s})$ and $u_{g\,max}=18.75(\mathrm{cm})$ are used here for the design moderate earthquakes. In equations (8a)-(8c), ω_U and ω_L are obtained from the following equations respectively:

$$S_D^A(\omega_U;h)=S_D^V(\omega_U;h) \quad , \quad S_D^V(\omega_L;h)=S_D^D(\omega_L;h) \tag{9a,b}$$

Consider four 20-story 3-span planar steel frames as shown in Fig. 2. Damper configuration of each model is as follows: Model ND is a pure frame with no damper; Model USD has small size dampers of $c_j=26.0(\mathrm{kNs/cm})$ at center spans in all stories; Model CSD has small size dampers of $c_j=52.0(\mathrm{kNs/cm})$ at center spans from the 2nd to the 11th story; Model ULD has large size dampers of $c_j=52.0(\mathrm{kNs/cm})$ at center spans in all stories. Note that the terms 'small' and 'large' mean not the magnitude of damping coefficient of each damper but that of total value of dampers in all stories, and that the totals of damping coefficients are identical between Model USD and Model CSD. Other parameters are: $E=2.06\times10^4(\mathrm{kN/cm^2})$; $\bar{\delta}_j=h_j/300$; $\bar{\varepsilon}_i=0.00157$; $\bar{A}_i^L=95.0(\mathrm{cm^2})$ for beams and $\bar{A}_i^L=291.0(\mathrm{cm^2})$ for columns; $\bar{A}_i^U=387.4(\mathrm{cm^2})$ for beams and $\bar{A}_i^U=1077.0(\mathrm{cm^2})$ for columns. Vertical load conditions are shown in Fig. 2. Structural damping ratio is assumed to be 2% for all modes.

Each beam and each column are assumed to be wide-flange section and box section, respectively. The second moments of area of beam I_B and column I_C and the modulus of section of beam Z_B and column Z_C are assumed to be expressed as

$$I_B=8.0A_B^{2.0} \quad , \quad I_C=1.2A_C^{2.0} \quad , \quad Z_B=1.5A_B^{1.5} \quad , \quad Z_C=0.80A_C^{1.5} \tag{10a-d}$$

in which the composite beam effect is take into consideration. The design variable grouping is used here for a specific group of members.

Design of Shear Models and Frame Models

First, based on *Step 1*, sets of story stiffnesses of shear building models and sets of horizontal design loads for corresponding frame models are computed. The computed design loads by eqn. (5) for frame models are shown in Fig. 3. Second, based on *Step 2*, sets of cross-sectional areas of frame models are found. Each designed model is to be called Model ND(0) and so on. Maximum interstory drifts of the designed frames are evaluated by extended CQC method and are shown in Fig. 4. Distributions of cross-sectional areas of Model ND are shown in Fig. 7(a). Distributions of the ratios of story shear deformations are shown in Fig. 5. It can be observed that the interstory drifts of Model ND(0) and those of Model CSD(0) satisfy the constraints (2a) within good accuracy of 5%, but those of Model USD(0) and those of ULD(0) do not. Thus, the design procedure for Model ND and Model CSD is terminated in this first cycle.

Model USD and Model ULD are re-designed. Ratios of story shear deformations to corresponding interstory drifts in Model USD(0) and Model ULD(0) are used for recalculation of damping coefficients of the shear models by eqn. (7). Re-designed models are to be called Model USD(1) and Model ULD(1). Maximum interstory drifts of re-designed frame models are shown in Fig. 6. It can be observed that the interstory drifts of Model USD(1) and those of Model ULD(1) satisfy the constraints (2a) within good accuracy of 5%. Thus the design procedure for Model USD and Model ULD is terminated in this second cycle. Distributions of cross-sectional areas of re-designed Model ULD are shown in Fig. 7(b).

The lowest damping ratio and total weight of structural members of each frame model are 2% and 244.5(ton) in Model ND(0), 3.3% and 201.0(ton) in Model USD(1), 4.2% and 196.2(ton) in Model CSD(0), 4.9% and 174.3(ton) in Model ULD(1), respectively, where the values of damping ratio contain structural damping. The reason why the damping ratios in Model USD(1) and Model CSD(0) are quite different despite that the totals of damping coefficients in both frame models are identical is that the damper performance in Model USD is reduced in upper stories by effect of overturning deformation. Note that total CPU time for each model is within 2 minute on PowerPC 333MHz.

Verification by Time-History Analysis

In order to demonstrate the validity of the proposed design method, time history analyses have been performed by Newmark-β method with time interval of 0.01(s) on the shear models corresponding to the designed frame models. A set of 10 artificial earthquake motions has been generated so as to be compatible with the specified design response spectrum with 2% damping ratio for the design moderate earthquakes. The duration of each artificial ground motion is 25.0(s). In Table 1, the distribution of floor masses, damping coefficients, story stiffnesses, and mean maximum interstory drifts in each shear building model are shown. It can be observed that the mean maximum interstory drifts in each model satisfy the constraints (2a) within good accuracy.

CONCLUSIONS

The conclusions may be summarized as follows:

(1) An optimum design method for a building frame with viscous dampers subject to earthquake response constraints has been proposed. The method consists of two steps. In the first step, a shear building model with viscous dampers is used and story stiffnesses are determined via inverse problem formulation so that the designed shear building would exhibit specified distribution of interstory drifts under design spectrum-compatible earthquakes. In the second step, an optimum set of cross-sectional areas of the frame model is determined subject to constraints on interstory drifts and member-end strains under a set of design horizontal loads.
(2) Re-calculation method for damping coefficients of the shear building model has been proposed to take into consideration the effect of overturning deformation on damper performance at the design stage of the shear building model.
(3) Four frame models were designed via proposed design method. It has been shown through the design examples that the method is highly efficient for optimum design for building frame with viscous dampers.

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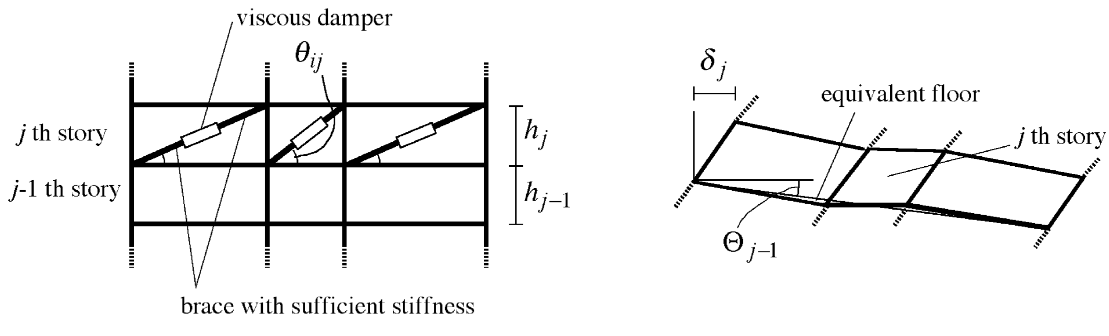


Figure 1. Damper installation in frame model, and definition of θ_{ij} and Θ_j

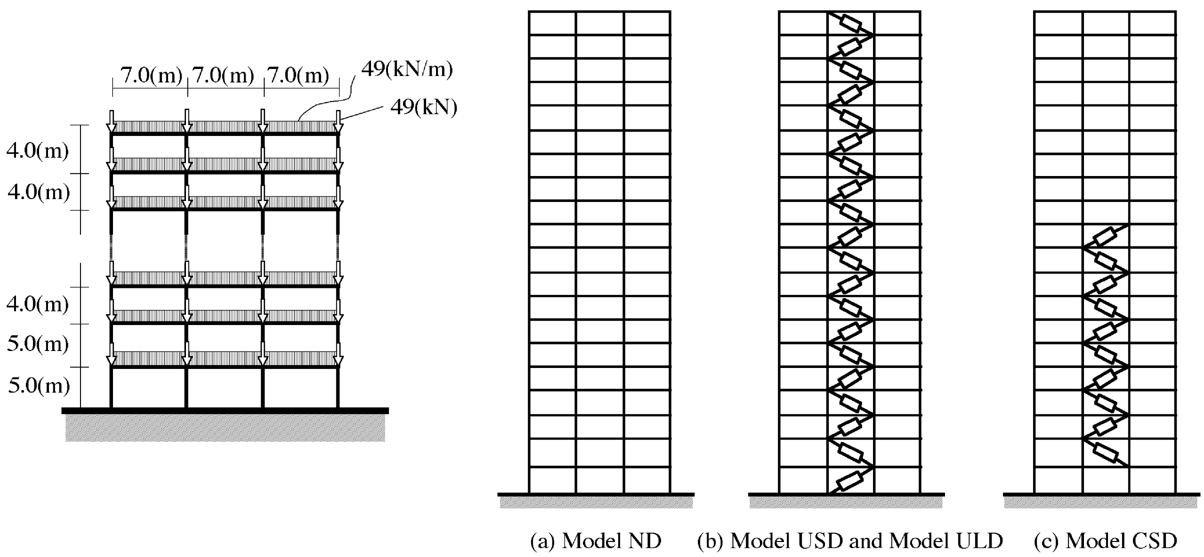


Figure 2. 20-story building frame structures with/without viscous dampers

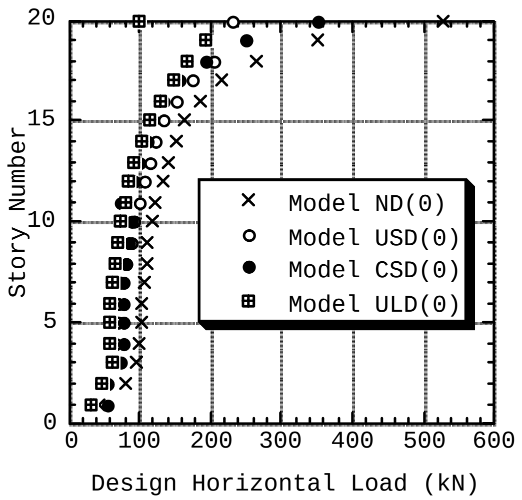


Figure 3. Distributions of design horizontal loads for each model

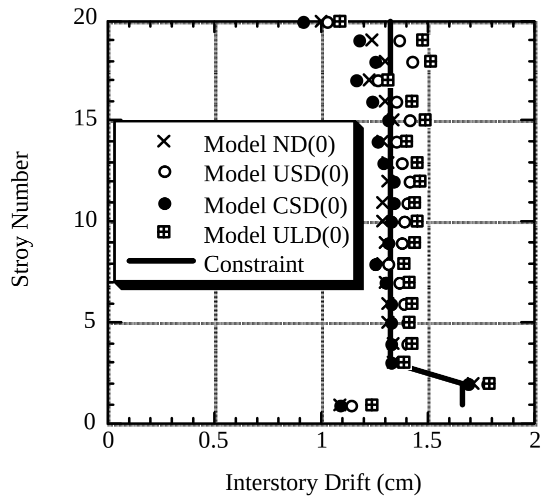


Figure 4. Distributions of maximum drifts in initial designed models under design earthquakes

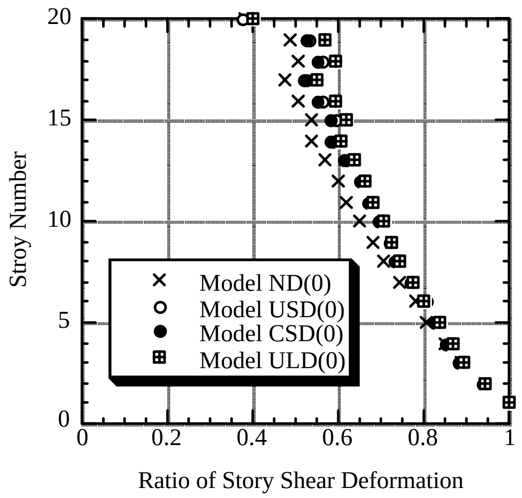


Figure 5. Distributions of ratios of shear deformation to interstorydrift in initial designed models

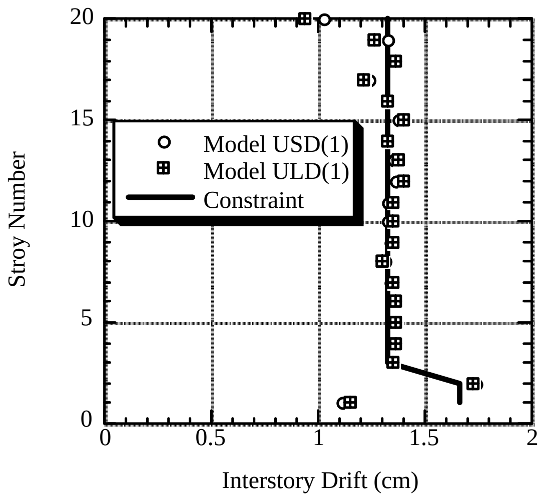
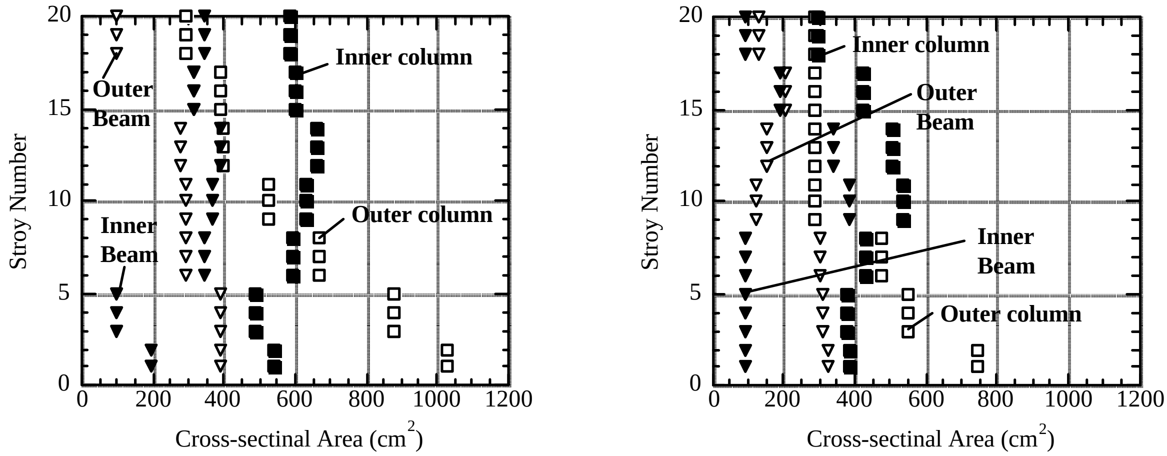


Figure 6. Distributions of maximum drifts in re-designed models under design earthquakes



(a) Model ND(0) **(b) Model ULD(1)**

Figure 7. Distributions of cross-sectional areas of Model ND(0) and Model ULD(1)

Table 1. Floor masses (ton), story stiffnesses (kN/cm), damper damping coefficients (kNs/cm), and mean maximum interstory drifts under spectrum-compatible 10 artificial earthquake motions

			Model ND(0)		Model USD(1)			Model CSD(0)			Model ULD(1)		
j	m_j	$\bar{\delta}_j$	$k_j^{(0)}$	$\delta_{j\,max}$	$k_j^{(1)}$	$\tilde{c}_j^{(1)}$	$\delta_{j\,max}$	$k_j^{(0)}$	$\tilde{c}_j^{(0)}$	$\delta_{j\,max}$	$k_j^{(1)}$	$\tilde{c}_j^{(1)}$	$\delta_{j\,max}$
1	125.0	1.67	3053.2	1.04	2244.5	17.2	1.06	2153.8	0.00	1.09	1752.7	34.4	1.10
2	125.0	1.67	1906.4	1.64	1427.5	16.2	1.64	1355.5	34.4	1.67	1152.8	32.3	1.63
3	125.0	1.33	2353.8	1.30	1776.3	17.3	1.30	1677.8	39.2	1.33	1427.8	34.8	1.29
4	125.0	1.33	2263.3	1.32	1700.3	16.8	1.33	1606.3	39.2	1.35	1366.2	33.6	1.33
5	125.0	1.33	2215.6	1.31	1651.0	16.3	1.34	1548.0	39.2	1.37	1317.1	32.6	1.35
6	125.0	1.33	2110.2	1.33	1591.7	15.7	1.35	1490.0	39.2	1.38	1271.6	31.6	1.35
7	125.0	1.33	2032.0	1.33	1535.7	15.0	1.36	1447.4	39.2	1.37	1233.3	30.4	1.35
8	125.0	1.33	1967.5	1.31	1507.4	14.4	1.34	1445.1	39.2	1.31	1225.6	29.1	1.30
9	125.0	1.33	1869.4	1.32	1412.4	14.0	1.37	1315.0	39.2	1.38	1126.8	28.4	1.36
10	125.0	1.33	1799.5	1.30	1354.5	13.5	1.35	1255.0	39.2	1.37	1098.0	27.5	1.33
11	125.0	1.33	1723.7	1.29	1293.4	12.9	1.34	1189.5	39.2	1.38	1040.6	26.6	1.33
12	125.0	1.33	1604.3	1.30	1192.1	12.6	1.37	1130.7	0.00	1.38	946.85	26.2	1.37
13	125.0	1.33	1519.6	1.29	1126.7	12.1	1.36	1094.7	0.00	1.34	897.84	25.1	1.34
14	125.0	1.33	1437.2	1.27	1062.7	11.5	1.32	1040.7	0.00	1.30	849.72	24.0	1.30
15	125.0	1.33	1283.9	1.29	922.96	11.5	1.37	903.43	0.00	1.36	720.90	24.3	1.37
16	125.0	1.33	1190.6	1.24	844.34	10.9	1.31	842.67	0.00	1.30	659.52	23.1	1.30
17	125.0	1.33	1097.4	1.15	773.39	10.1	1.21	778.12	0.00	1.21	600.72	21.3	1.19
18	125.0	1.33	857.73	1.18	570.18	10.9	1.30	597.11	0.00	1.27	413.29	23.2	1.34
19	125.0	1.33	679.78	1.05	425.41	10.5	1.22	474.97	0.00	1.14	300.73	21.8	1.26
20	125.0	1.33	492.02	0.77	283.78	7.95	0.962	351.50	0.00	0.816	178.54	15.4	1.08