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INELASTIC RESPONSE CONSTRAINED DESIGN OF SHEAR BUILDINGS VIA ELASTIC RESPONSE CONSTRAINED DESIGN

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SUMMARY

It is shown that the shear buildings designed for a prescribed uniform spectral interstory drift by the method of Nakamura and Yamane exhibit fairly regular mean maximum responses and only slightly nonlinear behaviors when subjected to major earthquakes compatible with the response spectrum with the level twice as large as that for design moderate earthquakes. Two new measures of plastic deformation are introduced here and several empirical formulas are derived with respect to a design condition parameter. The essential flows of two methods of inelastic response constrained design via those formulas are described.

INTRODUCTION

An efficient and direct method of earthquake-response constrained design has been presented by Nakamura and Yamane (Ref.1) for shear building models. Their method enables a designer to find a set of story stiffnesses such that the distribution of the mean maximum interstory drifts in a shear building model subjected to design moderate earthquakes compatible with a prescribed design spectrum would be equal to a specified one. The efficiency and validity of their method have been demonstrated by design examples and the result of time history analysis. A uniform shear building model designed by their method will be referred to simply as a shear building of ERCD design.

The purpose of this paper is to present first the results of time history analysis of shear buildings of ERCD design subjected to major earthquakes compatible with the response spectrum with the level twice as large as that for design moderate earthquakes and secondly a method of designing shear buildings so as to exhibit a desired distribution of mean maximum interstory drifts under design major earthquakes.

While some better stiffness and strength distributions have been found in several previous numerical experiments on shear buildings which would result in fairly uniform distributions of maximum inelastic responses under a set of design major earthquakes, no efficient and direct or quasi-direct method of design appears to have been proposed so far which would enable a designer to adjust or control the distributions of mean maximum inelastic responses of shear buildings under spectrum-compatible design major earthquakes.

CHARACTERISTIC INELASTIC RESPONSES OF SHEAR BUILDINGS OF ERCD DESIGN

Shear Buildings of ERCD Design Table I shows the stiffness coefficients to be multiplied by $m\Omega_1$ of the shear buildings of ERCD design. Table II shows the standard story displacement factors $\{\tilde{u}_j\}$(to be multiplied by T_1) which give twice as large as the mean maximum elastic story displacements $\{U_j\}$. The following set of displacement design spectra for assumed damping ratio of 2% has been adopted

Table I
Stiffness coefficients to be multiplied by $m\Omega_1$

Story no.	f=10	f=15	f=20
20			26.6
19			47.4
18			65.2
17			81.0
16			95.3
15		18.5	108.3
14		33.1	120.2
13		45.4	131.4
12		56.3	141.8
11		65.9	151.6
10	11.3	74.7	160.7
9	20.1	82.7	169.3
8	27.5	90.1	177.3
7	33.9	96.7	184.6
6	39.5	102.8	191.2
5	44.3	108.1	197.1
4	48.3	112.6	202.1
3	51.6	116.2	206.1
2	53.8	118.8	208.9
1	55.0	120.2	210.4

Table II
Displacement factors to be multiplied by T_1

Story no.	f=10	f=15	f=20
20			32.12
19			30.74
18			29.30
17			27.83
16			26.32
15		32.01	24.77
14		30.09	23.21
13		28.09	21.61
12		26.05	20.00
11		23.98	18.38
10	31.68	21.86	16.73
9	28.66	19.72	15.08
8	25.57	17.56	13.42
7	22.43	15.39	11.75
6	19.27	13.21	10.08
5	16.07	11.01	8.40
4	12.87	8.81	6.72
3	9.65	6.61	5.04
2	6.44	4.41	3.36
1	3.22	2.20	1.68

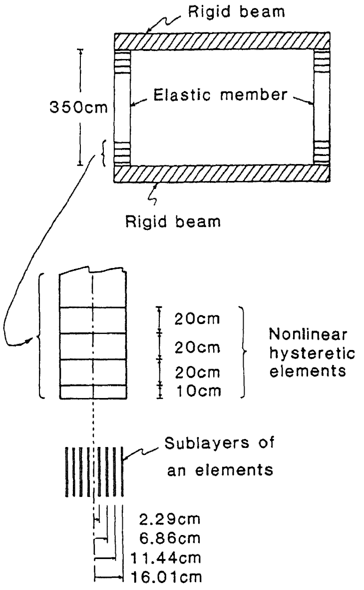

Figure 1
Finite elements and sublayers

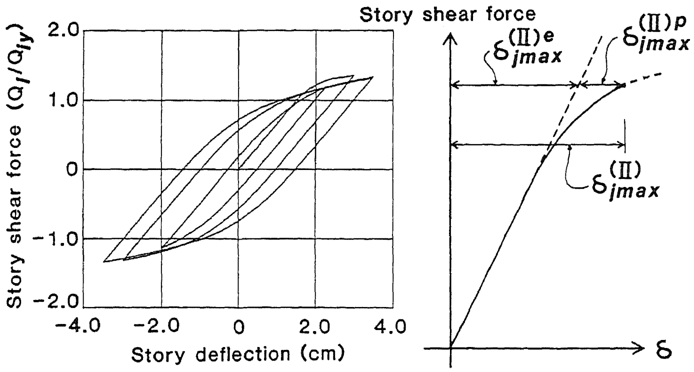

Figure 2
A typical hysteresis curve and some response points on a slightly nonlinear region of a skeleton curve

for the design.

$$S_{D1}^{(I)}(T_1:0.02)=22.33T_1^{\,2} \quad (T_1<0.501) \tag{1a}$$
$$S_{D2}^{(I)}(T_1:0.02)=11.14T_1 \quad (T_1\geqq 0.501) \tag{1b}$$

The four classes of designs are characterized by the design interstory drifts $\bar{\delta}$ = 0.85cm, 1.00cm, 1.25cm, and 1.50cm.

A realistic building frame consisting of elastic-plastic members will exhibit fairly smooth inelastic hysteretic responses when subjected to design major earthquakes. The columns in the shear buildings defined by Table I are therefore assumed to obey the nonlinear hysteretic uniaxial stress-strain relations due to Yokoo and Nakamura (Ref.2). Figure 1 shows the finite elements and sublayers of each column. Each cross-section has been designed in such a way that the extreme fibers at each column end will attain the elastic limit when the maximum spectral interstory drift δ_{jmax} is equal to 1.5cm. A typical hysteresis curve and some response points are shown in Figure 2.

Design Major Earthquakes For the purpose of later derivation of behavioral formulas and for development of inelastic response-constrained design procedure, the shear buildings of ERCD design have been subjected to ten major artificial earthquakes generated by the SIMQKE program(Ref.3) so as to be compatible with the target velocity response spectrum defined by the six points: $(T(\mathrm{s}),S_V(\mathrm{cm/s}))$ =(0.02,1.31),(0.05,3.26),(0.125,35.1),(0.50,140),(3.10,140) and (5.00,85.9). This

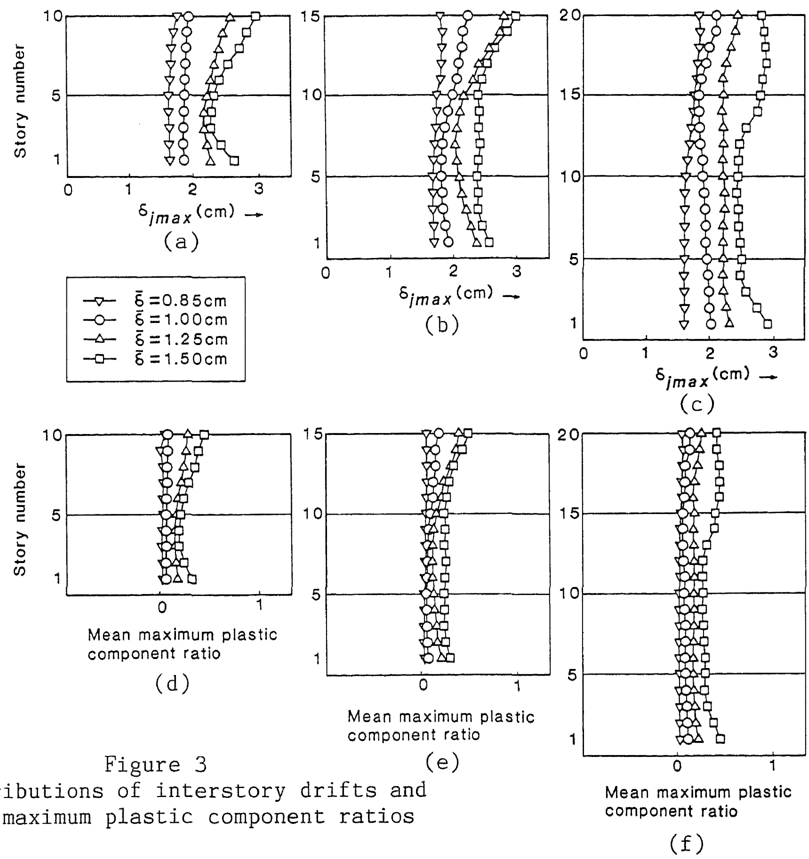

Figure 3
Distributions of interstory drifts and mean maximum plastic component ratios

target spectrum is for systems with 2% of critical damping and is of the level twice as large as that of $S_D(T;h)$ in Equation.(1).

Method of Inelastic Response Analysis A computer program for combined non-linear dynamic analysis of steel frames developed by Nakamura, Kosaka and Kitada (Ref.4) on the basis of the static version by Nakamura,Kamagata and Kosaka (Ref.5) has been utilized for time history analysis of the twelve shear buildings.

Mean Maximum Responses Figure 3(a),(b)and(c) show the story-wise distributions of mean maximum inelastic interstory drifts $\delta_{jmax}^{(II)}$. It is apparent that the distribution in a shear building designed for a smaller value of $\bar{\delta}$ is more nearly uniform. The average $\bar{\delta}_m$ of $\{\delta_{jmax}^{(II)}\}$ over all the stories in each shear building is slightly smaller than twice the value $\bar{\delta}$ specified for the building under the design moderate earthquakes. Since all the columns in each shear building have been designed so as to attain their elastic limit when $\delta_{jmax}^{(II)}$=1.5cm,the plots in Figure 3(a),(b)and(c) can be interpreted as those representing story-wise distributions of mean maximum ductility factors with respect to the elastic limit provided that the abscissa is divided by 1.5cm.

The hollow triangular,circular and square marks in Figure 4 show an example of the story-wise plots of mean maximum inelastic story displacements. The black triangular, circular and square marks therewith are the story-wise plots of elastically predicted story displacements which are twice as large as those under moderate earthquakes to be compared with the former. It is almost apparent that each of the former plots may be represented as a multiple of the latter with a fairly good accuracy. The multiplier representing inelastic response with respect to elastically predicted story displacements for a shear building is called inelastic response displacement factor here and is denoted by ν_p. The ν_p values for almost all the shear buildings are less than 1.0.

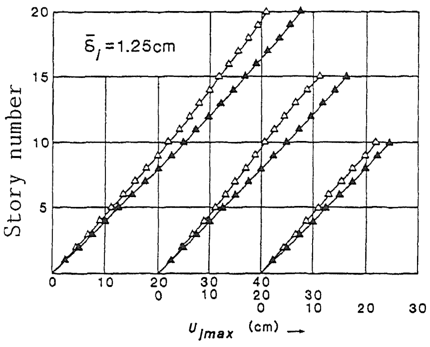

Figure 4

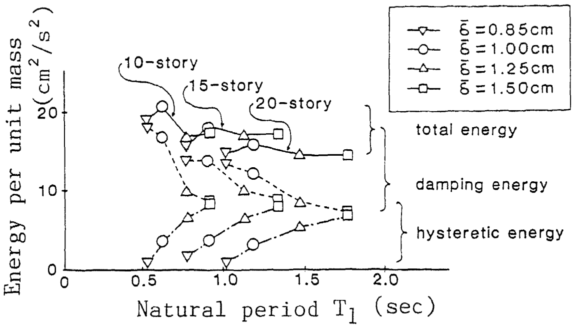

Figure 5

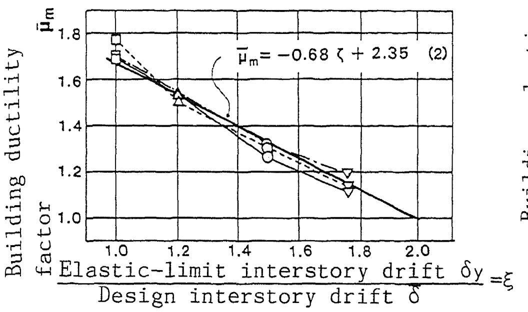

Figure 6

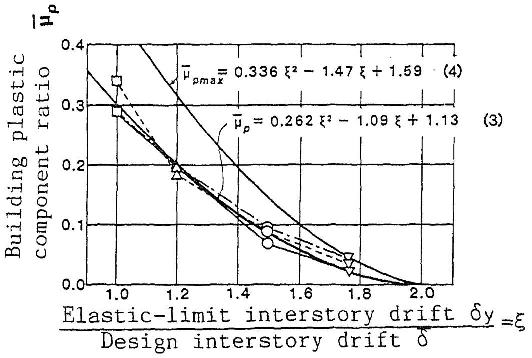

Figure 7

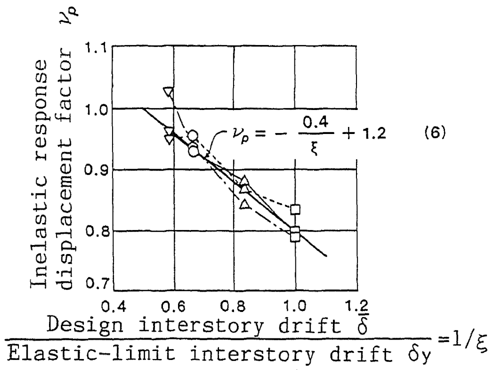

Figure 8

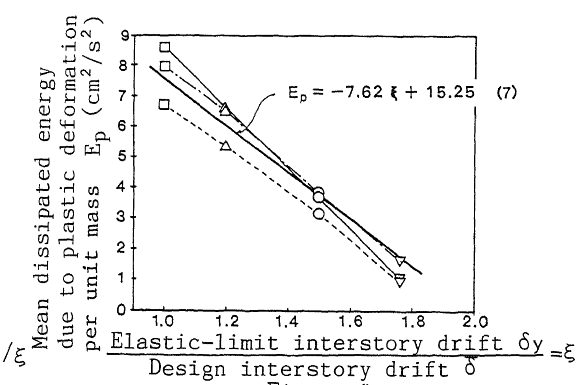

Figure 9

Figure 5 shows the plots of the mean total input energy, the mean dissipated energy due to viscous damping and the mean dissipated energy due to plastic deformation per unit mass with respect to the fundamental natural period T_1. It should be noticed in these figures that the amounts of mean total input energy in shear buildings of the same number of stories are almost equal irrespective of the specified values of $\bar{\delta}$. It can also be observed that, while the amounts of mean dissipated energy due to plastic deformation are almost equal for shear buildings with an equal value of $\bar{\delta}$ irrespective of the number of stories, the amounts of mean dissipated energy due to viscous damping and of the corresponding mean total input energy through those shear buildings with an equal value of $\bar{\delta}$ appear to be almost gradually decreasing with respect to T_1. In every shear building, the amount of dissipated energy due to viscous damping is greater than that due to plastic deformation.

TWO NEW MEASURES OF INELASTIC RESPONSES AND EMPIRICAL FORMULAS

In view of the characteristic response behaviors of the shear buildings of ERCD design, it appears appropriate to define the following two new measures (μ_{pj} and ν_p) of their inelastic deformation. Since the mean maximum ductility factors μ_{mj} for every shear building are fairly uniformly distributed as observed from Figure 3, the average $\bar{\mu}_m$ of $\{\mu_{mj}\}$ over all the stories of a shear building may be adopted as an overall measure of inelastic deformation and will be called "building ductility factor". On the other hand the ratio of the uniform elastic-limit interstory drift δ_y to the design interstory drift $\bar{\delta}$ for the prescribed design spectrum (1) is adopted as a representative index of the design condition and is denoted by ξ. Figure 6 shows the plots of $\bar{\mu}_m$ values of 10,15 and 20 story shear buildings with respect to ξ. The best-fit straight line through the three classes of plots and through (2.0,1.0) is expressed by

$$\bar{\mu}_m=-0.68\xi+2.35 \tag{2}$$

Mean Maximum Plastic Component Ratio and Building Plastic Component Ratio

The restoring force-drift curve and the skeleton curve of a realistic multi-span frame are both fairly smooth as represented or modeled by those of the columns in a present shear building model and the response points on those curves are mostly within a region which deviates only slightly from the straight line of initial elastic stiffness. The mean ductility factor μ_{mj} may not be an accurate measure of inelastic deformation for such a slightly nonlinear response. It seems more appropriate to introduce the plastic component $\delta_{jmax}^{(II)p}$ of a mean maximum interstory drift by subtracting the elastic component from the total as shown in Figure 2. The ratio μ_{pj} of the plastic component to the corresponding elastic component of a mean maximum interstory drift in the j-th story is defined as a better measure and is called "mean maximum plastic component ratio". Figure 3(d),(e) and (f) show the story-wise plots of $\{\mu_{pj}\}$. It is apparent that the distributions of $\{\mu_{pj}\}$ are more nearly uniform for all the shear buildings. The average $\bar{\mu}_p$ of $\{\mu_{pj}\}$ values over all the stories of a shear building may also be adopted as an overall measure of inelastic deformation and will be called " building plastic component ratio". Figure 7 shows the plots of $\bar{\mu}_p$ values with respect to ξ. A best-fit curve through the three classes of plots may be expressed by

$$\bar{\mu}_p=0.262\xi^2-1.09\xi+1.13 \tag{3}$$

It is also desirable to plot the maximum values of the set of μ_{pj}'s with respect to ξ. A best-fit curve has been drawn in Figure 4 and may be expressed by

$$\bar{\mu}_{pmax}=0.336\xi^2-1.47\xi+1.59 \tag{4}$$

Inelastic Response Displacement Factor All the plots similar to Figure 4 for the twelve models indicate that the mean maximum story displacement D_j can be expressed as the product of the elastically predicted story displacement U_j and the multiplier ν_p. The ν_p value for a shear building may be defined as follows by minimizing the sum of the squares of the deviations of $\nu_p U_j$ from D_j;i.e.

$$\nu_p=\sum_{j=1}^{f}(U_jD_j)/\sum_{j=1}^{f}U_j^2 \tag{5}$$

Figure 8 shows the plots of ν_p values with respect to $(1/\xi)$. The best-fit straight line through the plots and through the elastic-limit point (0.5,1.0) is given by

$$\nu_p=-0.4/\xi+1.2 \tag{6}$$

Mean Dissipated Energy due to Plastic Deformation Figure 9 shows the plots of mean dissipated energy due to plastic deformation E_p with respect to ξ. The best-fit straight line through the plots and through (2.0,0.0) is expressed by

$$E_p=-7.62\xi+15.25 \tag{7}$$

METHODS OF INELASTIC RESPONSE CONSTRAINED DESIGN VIA EMPIRICAL FORMULAS

The set of empirical formulas (2)-(7) for the present shear building models has a generality of only a limited range. Yet the essential flow of a method of inelastic response constrained design can be formed or developed on the basis of the set of those formulas. The design information consisting of a set of story stiffnesses and a set of elastic limit displacements for a shear building model can be utilized as a central guideline with reference to which the stiffnesses and strengths of the members of a realistic frame can be designed. The idea and essential flow of the proposed procedure can be extended toward a direct design procedure of a class of realistic frames provided that a similar set of empirical formulas are derived through an extensive numerical experiments on realistic frame models of that class.

It should also be noted that the following two flows of direct inelastic design are developed on the basis of the following two restrictions:
(i) design earthquakes compatible with the following simplified design spectra
(ia) Level I Spectrum (for moderate earthquakes) is given by equation(1).
(ib) Level II Spectrum (for major earthquakes) is given by $2S_{D1}{}^{(I)}$ and $2S_{D2}{}^{(I)}$.
(ii) almost uniform distributions of various response quantities.
In a realistic design, the designer may wish to prescribe some smaller values of μ_{pj} for several stories from the base and from the top. In such a case, the following flows need to be slightly modified on the basis of some modified overall inelastic response measures.

Problem BPCR Given$\{m_j\}$, $\bar{\delta}$, design building plastic component ratio $\bar{\mu}_D$ and deviation parameter α , for a shear building, find $\{k_j\}$ and δ_y such that

$\delta_{jmax}{}^{(I)} = \bar{\delta}$ $(j=1\cdots f)$ (B1) $\bar{\mu}_{pmax} \leqq \alpha\bar{\mu}_D$ (B2) and $\bar{\mu}_p \leqq \bar{\mu}_D$ (B3)

Solution Procedure All the constraints (B1) are satisfied by $\{k_j\}$ of ERCD design. Then the value of ξ corresponding to $\bar{\mu}_D$ is found with equation (3) and δ_y can be computed. (B2) is checked by utilizing equation (4). If (B2) is not satisfied, the value of ξ corresponding to (B2) is first determined by use of equation (4). Then (B3) is satisfied as an inequality.

Problem IRDF Given $\{m_j\}$, $\bar{\delta}$ and design story displacement distribution $D_{jD}=\nu_D\tilde{u}_jT_1$ in terms of a specified multiplier ν_D, find $\{k_j\}$ and δ_y such that

$\delta_{jmax}{}^{(I)} = \bar{\delta}$ $(j=1\cdots f)$ (D1) and $\nu_p = \nu_D$ (D2)

Solution Procedure (D2) requires that all the story displacement D_j under design major earthquakes must be approximately equal to D_{jD} in the sense of the least square fitting. As the first step of the solution procedure is the same as in the previous problem BPCR, D_{jD} is determined in terms of T_1. The corresponding value of ξ and δ_y can be found from equation (6).

CONCLUSIONS

It has been found that the uniform shear buildings of ERCD design (Ref.1) for a prescribed uniform spectral interstory drift exhibit fairly regular mean maximum responses and only slightly nonlinear behaviors when subjected to major earthquakes compatible with the response spectrum with the level twice as large as that for design moderate earthquakes. The mean maximum plastic component ratio and building plastic component ratio have been defined as more accurate measures of plastic deformation in a story and in a shear building, respectively. The inelastic response displacement factor has also been introduced as a multiplier for predicting story displacements under design major earthquakes. Several empirical formulas have been derived with respect to a design condition parameter.

While generality of those empirical formulas is restricted only to shear buildings of ERCD designs, it has been shown that the essential flows of two methods of inelastic response constrained design can be developed with reference to those empirical formulas. The essential flows may be extended to more realistic cases.

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