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INELASTIC DISPLACEMENT DEMANDS FOR STRUCTURES BUILT ON SOFT SOILS

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ABSTRACT

A procedure to estimate inelastic displacement demands for structures built on soft soil records when subjected to earthquake ground motions is presented. Emphasis is given to the estimation of lateral displacement demands and interstory drift demands. The study is based on 32 ground motions recorded on soft soil deposits in Mexico City. Inelastic displacement demands are computed from elastic displacement demands of single-degree-of-freedom systems through the use of inelastic displacement ratios. Additionally, for the case of multi-degree-of-freedom systems a relationship between global and local deformation demands based on nonlinear static analysis is used. Analytical expressions to compute the ratio of inelastic to elastic displacements are proposed as a function of the displacement ductility ratio and the ratio between the period of the structure and the predominant period of the ground motion. The procedure is tested by comparing maximum computed inelastic roof displacement demands and inelastic interstory drift demands with those computed with detailed nonlinear time history analyses of three reinforced concrete moment-resisting frame buildings. Results indicate that the procedure produces good estimates of inelastic displacement demands.

KEYWORDS

Displacement-based seismic design criteria; soft soil; inelastic displacement ratios; interstory drift demands; equivalent SDOF system.

INTRODUCTION

The primary design parameter in current seismic design provisions is the lateral strength demand and displacement limits are checked near the end of the design process for serviceability limits. However, structural damage is primarily the result of lateral displacements, thus, adequate damage control can be achieved by using displacements as the primary design parameter. Recently there has been a growing interest in displacement-based seismic design procedures (Moehle, 1992; Wallace, 1995; Calvi and Kingley, 1995; Kowalsky, et al., 1995), however these studies have been oriented to the design of structure built on rock or firm soil deposits. Furthermore, these studies have put emphasis on conceptual aspects of the design process and not on the estimation of displacements demands. The objective of this paper is to present a procedure to estimate inelastic displacement demands on structures built on soft soil deposits.

INELASTIC DISPLACEMENT DEMANDS

The proposed procedure is based on the explicit consideration of inelastic behavior and on the use of an equivalent single-degree-of-freedom (SDOF) system to model the behavior of multi-degree-of-freedom (MDOF) systems. The first step of the procedure consists on the estimation of the inelastic displacement demand of a SDOF system. Most methods available to estimate inelastic displacement demands have recognized the advantages of estimating inelastic displacement demands in terms of elastic displacement demands. Existing displacement-based design criteria have assumed that inelastic displacements demands are the same as elastic displacement demands (Wallace, 1995) or have assumed that the inelastic displacement demand of a SDOF system can be estimated by the elastic displacement demand on an equivalent system with a smaller stiffness and a larger damping ratio (Calvi and Kingley, 1995; Kowalsky, et al., 1995). The change in stiffness and damping is computed as a function of the displacement ductility ratio. The basis of the first study is the "equal displacement rule" whereas the latter studies are based on the so-called "substitute structure approach" (Shibata and Sozen, 1976).

In the proposed method the inelastic displacement demand is obtained as the product of the elastic displacement demand times an *inelastic displacement ratio* which is defined as the ratio of the inelastic to elastic displacement demand. Very early studies recognized that in the low-frequency and medium-frequency regions the maximum deformation of the elastic system may be considered to be the same as the maximum deformation of the inelastic system, and that in the high frequency range inelastic displacements are larger than elastic ones (Veletsos and Newmark, 1961). A literature review on previous studies of the effects of nonlinear seismic behavior of SDOF systems has been presented by Miranda (1991). Based on a comprehensive statistical study of inelastic behavior of SDOF systems when subjected 124 ground motions recorded in different soil conditions, Miranda (1993) concluded that for long-period systems on rock or firm alluvium sites, the mean inelastic displacement ratio is approximately 1. However, the study also concluded that the periods limiting the use of the "equal displacement rule" depend on the soil conditions and the level of inelastic deformation. An example of the results of this previous study are shown in Fig. 1 which shows mean inelastic displacement ratios of SDOF systems undergoing displacement ductility ratios of 2, 4 and 6 when subjected to earthquake ground motions recorded on firm alluvium sites. It can be seen that for a ductility ratio of 2 the inelastic displacement demands are approximately the same as the elastic displacement demands for periods greater than 0.4 s, while for a ductility ratio of 6 such assumption is only valid for period greater than about 1.0 s.

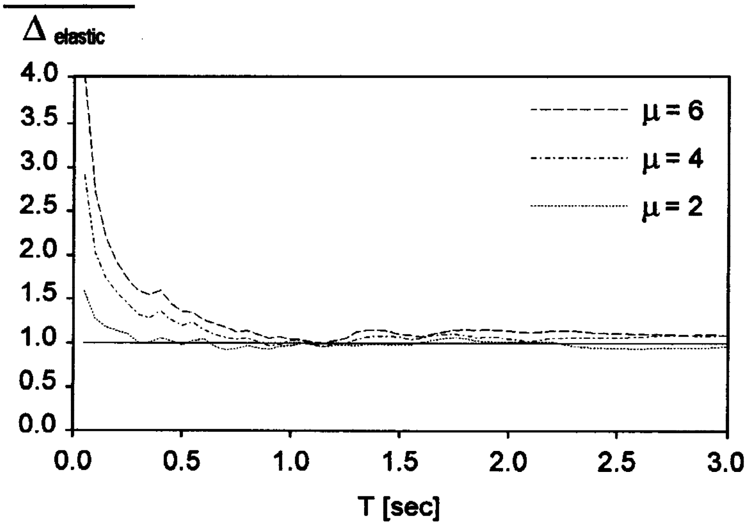

Fig. 1. Mean inelastic displacement ratios for ground motions recorded on firm alluvium sites.

For structures on soft soil the same study concluded that inelastic displacement ratios are strongly dependent on the ratio of the period of the structure, T, to the predominant period of the ground motion T_g. The study was based on 22 ground motions recorded in "bay-mud" deposits of the San Francisco Bay Area (SFBA), and soft soil deposits of Mexico City and 2 motions recorded in Bucharest. Results of the study showed that for periods near the site-predominant period T_g, the maximum inelastic displacement can be on average up to 45% smaller than the maximum elastic displacement. On the other hand, for periods T smaller than two-thirds T_g, the inelastic displacements are significantly larger. The smaller the T/T_g ratio, the larger the difference is and tends to be proportional to the displacement ductility ratio. For structures with periods longer than 1.5 times the predominant period of the site, the inelastic displacements are on average equal to the elastic displacement. Similar conclusions were more recently obtained by Rahnama and Krawinkler (1993) who studied displacement demands produced by 6 soft soil ground motions recorded in the SFBA during the 1989 Loma Prieta earthquake.

In order to further study the inelastic displacement ratios in soft soil in this study a new set of ground motions was considered. The set consists exclusively of ground motions recorded in the old lake-bed of Mexico City and in the most severely damaged part of the city in the 1985 Michoacán earthquake. Complete listing of all recorded with their peak ground acceleration is shown in Table 1. For each record the maximum elastic and inelastic displacement demands were computed for a fix set of 50 T/T_g ratios. Inelastic displacement demands were computed by iteration on the yielding strength until the computed ductility demand was within 1% of the target ductility ratio. The following values of target ductilities were selected for this investigation: 1 (elastic behavior), 1.5, 2, 3, 4, and 5. The hysteretic behavior of the SDOF systems

Table 1. List of soft soil records used in this study.

STATION No.	STATION NAME	LAT. N°	LONG. W°	COMP.	DATE	PGA [cm/s2]
01	ALAMEDA	19.4356	99.1453	NS	25/ABR/89	45.95
				EW	25/ABR/89	37.52
03	C.U. JUAREZ	19.4098	99.1567	NS	25/ABR/89	40.72
				EW	25/ABR/89	37.68
05	CIBELES	19.4186	99.1653	NS	25/ABR/89	54.34
				EW	25/ABR/89	45.82
06	XOCHIPILLI	19.4198	99.1353	EW	25/ABR/89	43.55
				NS	25/ABR/89	57.24
08	TLATELOLCO	19.4500	99.1336	EW	25/ABR/89	32.35
				NS	25/ABR/89	47.55
08	TLATELOLCO	19.4500	99.1336	EW	24/OCT/93	8.38
				NS	24/OCT/93	8.10
09	VILLA GOMEZ	19.4539	99.1225	EW	25/ABR/89	38.21
				NS	25/ABR/89	47.41
19	MEYEHUALCO	19.3461	99.0433	EW	25/ABR/89	54.55
				NS	25/ABR/89	29.78
25	P.C.C. SUPERFICIE	19.2483	99.1444	EW	25/ABR/89	42.43
				NS	25/ABR/89	43.23
29	VILLA DEL MAR	19.3811	99.1253	EW	25/ABR/89	49.54
				NS	25/ABR/89	47.80
49	BUENOS AIRES	19.4097	99.1450	EW	25/ABR/89	54.52
				NS	25/ABR/89	58.97
56	CORDOBA	19.4215	99.1590	EW	25/ABR/89	73.00
				NS	25/ABR/89	39.10
95	SCT-B2	19.3930	99.1470	NS	25/ABR/89	37.49
				EW	25/ABR/89	37.89
95	SCT-B2	19.3930	99.1470	NS	24/OCT/93	11.74
				EW	24/OCT/93	10.54
95	SCT-B2	19.3930	99.1470	NS	19/SEP/85	97.85
				EW	19/SEP/85	167.92
DFRO	ROMA	19.4050	99.1660	NS	25/ABR/89	54.55
				EW	25/ABR/89	29.78

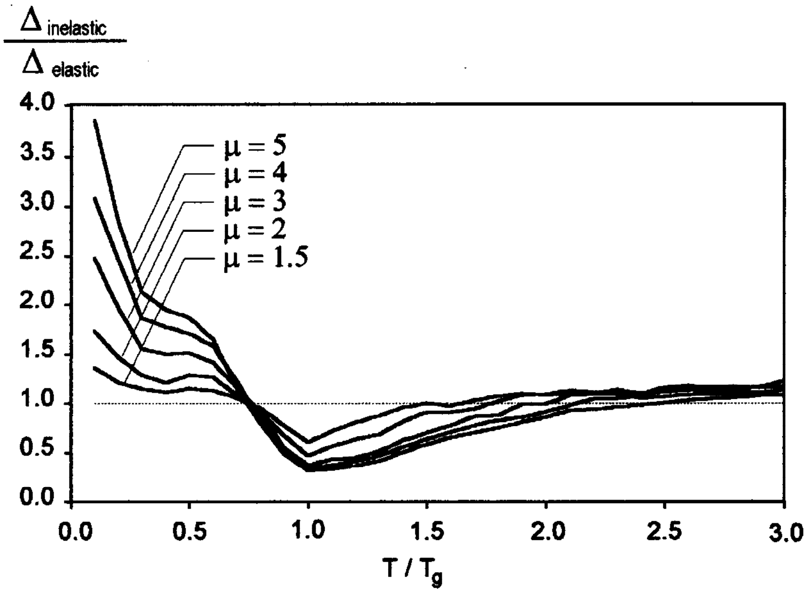

Fig. 2. Mean inelastic displacement ratios for ground motions recorded on soft soil sites.

analyzed corresponds to an elastic-perfectly plastic type. A total of 8,000 inelastic displacement ratios were computed (product of 32 ground motions, 50 T/T_g ratios and five levels of displacement ductility). For each T/T_g ratio and each level of inelastic deformation mean inelastic displacement ratios were obtained. Fig. 2 shows these results. It can be seen that for a system with a period equal to the predominant period of the ground motion (i.e., T/T_g=1) the elastic displacement demands are on average 1.6 times larger and 3 times larger than the inelastic displacement demands for displacement ductility ratios of 1.5 and 5, respectively, and that for this set of ground motions the equal displacement rule is only approximately valid for periods larger than two times the predominant period of the ground motion.

REGRESSION ANALYSES

For practical applications, a simplified expression is desired to relate the inelastic displacement ratio to the displacement ductility ratio, μ. Thus, the inelastic displacement demand can be estimated by multiplying the elastic displacement demand by the inelastic displacement ratio. Regression analyses were conducted in order to obtain a simplified analytical expression to obtain the inelastic displacement ratio as a function of the T/T_g ratio and μ. The proposed analytical expression is as follows:

$$\frac{\Delta_{inelastic}}{\Delta_{elastic}} = a + b\,\frac{T_g}{T} - c\,\frac{T_g}{T}\,exp\left[-d\left(Ln\frac{T}{T_g} - e\right)^2\right] \tag{1}$$

where a, b, c, d, and e are constants which depend on the level of inelastic deformation. The value of these coefficients that produce best fits with mean inelastic displacement ratios obtained from the statistical analysis are listed in Table 2. A comparison between mean values and those computed with equation 1 is shown in Fig. 3. It can be seen that, in general, the analytical expression is good. From figures 1, 2 and 3 it is clear that inelastic displacement ratios are strongly dependent on the local site conditions, the level of inelastic deformation and on the period of vibration T, or the ratio of the period of the structure to the predominant period of the ground motion T/T_g.

Table 2. Coefficients to compute inelastic displacement ratios.

μ	a	b	c	d	e
1.5	1.06	0.03	0.50	18.00	0.05
2.0	1.10	0.06	0.75	12.00	0.10
3.0	1.10	0.17	1.00	5.00	0.15
4.0	1.10	0.26	1.15	4.50	0.20
5.0	1.00	0.37	1.20	4.50	0.20

ESTIMATION OF INELASTIC DISPLACEMENT DEMANDS OF MDOF SYSTEMS

To obtain the inelastic displacements demands on MDOF systems the proposed method is based on the use of an equivalent SDOF model. Several methods for developing an equivalent SDOF system from a MDOF system have been proposed in the literature (Biggs, 1964; Saiidi and Sozen, 1979). The adequacy of SDOF systems to estimate the global response of MDOF systems has been studied by several investigators (Saiidi and Sozen, 1979; Qi and Moehle, 1991; Miranda, 1991; Collins, 1995). The proposed method to estimate inelastic displacement demands of MDOF structures is the following: (1) Construct and calibrate linear and nonlinear mathematical models of the building; (2) Conduct nonlinear static-to-collapse (i.e., push-over) analysis of the building; (3) With the results of the static nonlinear analysis of the building, determine a relationship between the roof displacement and the maximum interstory drift index. This relationship is constant while the structure remains elastic but after strong nonlinearities occur it becomes a function of the level of global inelastic deformation (Miranda, 1996); (4) Develop an equivalent SDOF system of the MDOF

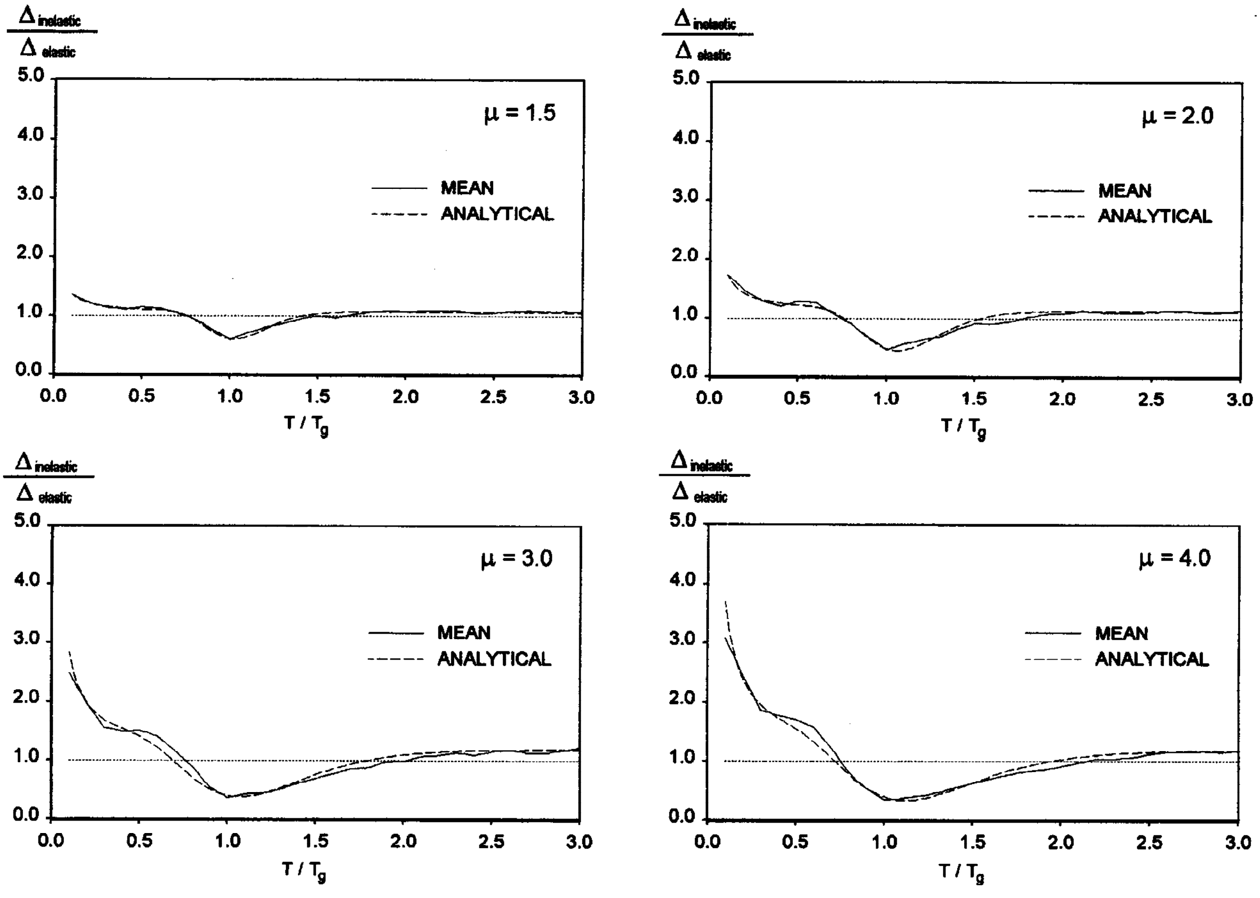

Fig. 3. Comparison of mean displacement ratios with those computed with the proposed expression.

model; (5) With a linear elastic response spectrum and the equivalent SDOF model, estimate the maximum roof displacement and with the relationship between global and local demands the maximum elastic interstory drift index is obtained; (6) With nonlinear response spectra, estimate the global displacement ductility ratio on the equivalent SDOF model; (7) With the relationship between global and local deformation demands and the inelastic displacement ratio, inelastic roof displacement and inelastic interstory drift index are obtained.

VALIDATION OF THE PROCEDURE

In order to evaluate the effectiveness of the proposed procedure, three moment-resisting reinforced concrete buildings were designed according to the Mexico City building code with 8, 12 and 16 stories. According to this code the design base shear coefficient is 0.133. The three buildings have the same plan which consists of three bays in each direction as shown in Fig. 4. The columns have a constant cross section whose dimensions are 80x80 cm, 85x85 cm, and 90x90 cm for the building with 8, 12 and 16 stories, respectively. The beams have a constant rectangular cross-section whose dimensions are 25x75 cm, 25x85 cm and 30x90 cm, for the building with 8, 12 and 16 stories, respectively. Such large cross sections are necessary to comply with the strict drift limitations of the 1993 Mexico City building code whose maximum allowed interstory drift index is 0.012. The computed fundamental period of vibration is 1.19 s, 1.57 s and 1.82 s for the building with 8, 12 and 16 stories, respectively.

Two-dimensional nonlinear static analyses were conducted for the three building using an inverted triangular lateral force profile. With the results of the nonlinear static analyses, the parameters of an equivalent SDOF model of each building were computed. Additionally, a relationship between the maximum roof displacement and maximum interstory drift index was obtained for different levels of lateral deformation. The proposed procedure was applied to each building when subjected to three earthquake ground motions recorded in Mexico. The first ground motion is the east-west component of the well-known SCT accelerogram recorded during the September 19, 1985 Michoacán earthquake; the second ground motion is the east-west of the Xochipilli ground motions recorded during the April 25, 1989 Guerrero earthquake and the third one is the north-south Roma ground motion also recorded during the April 25, 1989 Guerrero earthquake.

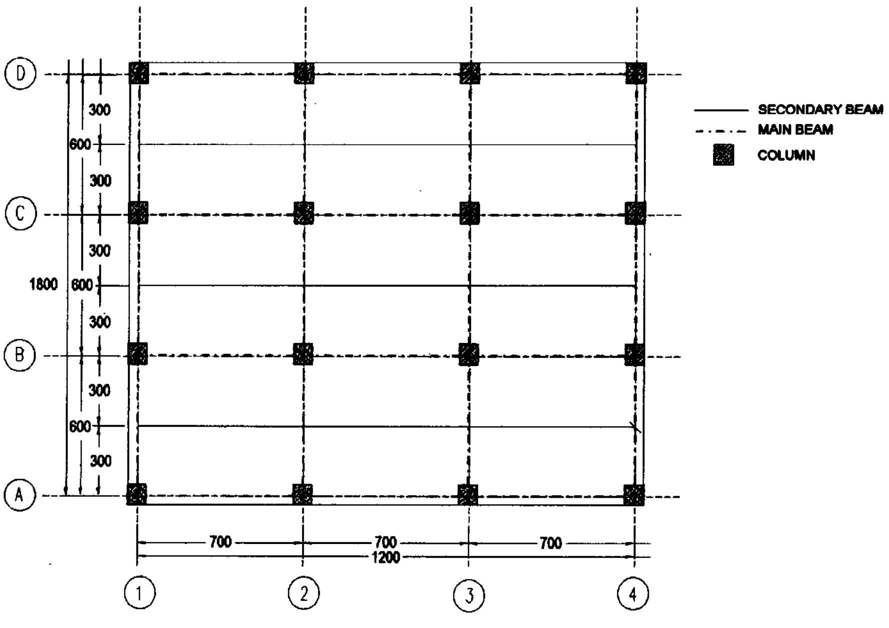

Fig. 4. Plan of the multi-story buildings analyzed in this study.

First, the maximum roof displacement and maximum interstory drift index was computed with the proposed procedure on each building assuming a linear-elastic behavior for each of the three ground motions. Then, the maximum roof displacement and maximum interstory drift index was computed on each building for story displacement ductility ratios of 3, 4 and 5 which correspond to strong nonlinearities when subjected to these three ground motions.

To evaluate the results of the proposed method, elastic and inelastic maximum roof displacements and maximum interstory drift index were computed in these buildings with two-dimensional nonlinear step-by-step time history analyses with the Drain-2d program. To compute inelastic displacements demands iteration on a scale factor to the intensity of the ground motion was performed until the local (i.e., story) displacement ductility was within one percent of the target ductility ratios of 3, 4 and 5.

A comparison of maximum roof displacements computed with detailed nonlinear time-history analyses of the buildings with those computed with the proposed procedure is shown in Fig. 5. The triangles correspond to computed responses assuming a linear elastic behavior and squares correspond to inelastic roof displacement demands of buildings with strong nonlinearities. It can be seen that for linear elastic behavior the proposed procedure produces excellent results, whereas for inelastic behavior a small overestimation is produced, however, the procedure gives good results from a practical point of view.

Fig. 6. shows a comparison of maximum interstory drift demands with detailed nonlinear time-history analyses of the buildings with those computed with the proposed procedure. It can be seen that, in general, the proposed method produced small underestimations of the maximum interstory drift, with slightly larger underestimations for strong nonlinearities (squares) than for linear-elastic local demands (triangles). In general, the error increases with the number of stories.

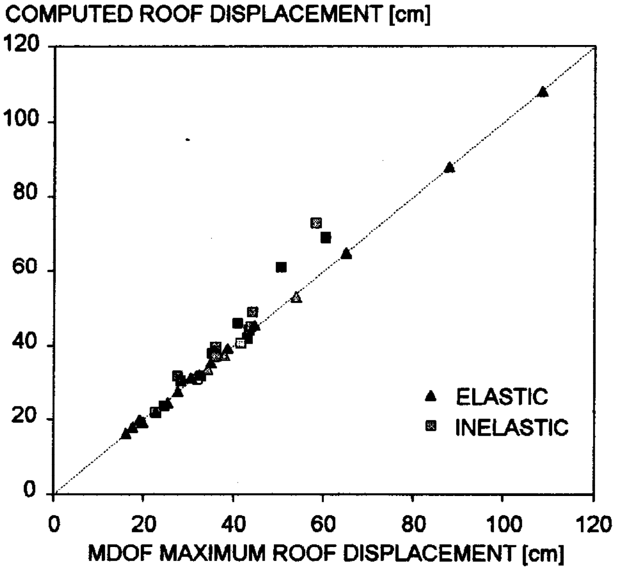

Fig. 5. Comparison of roof displacement demands computed in three buildings undergoing story ductility demands of 1, 3, 4 and 5 computed with MDOF nonlinear time history analyses with those computed with the proposed method.

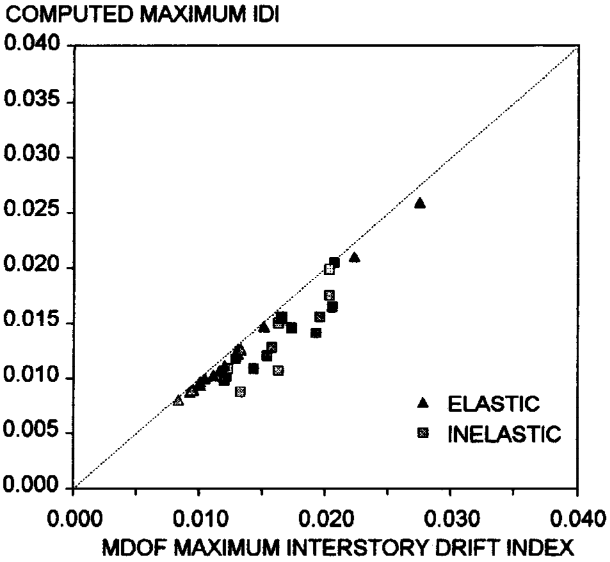

Fig. 6. Comparison of interstory drift index demands computed in three buildings undergoing story ductility demands of 1, 3, 4 and 5 computed with MDOF nonlinear time history analyses with those computed with the proposed method.

CONCLUSIONS

A procedure to estimate inelastic displacement demands for structures built on soft soil records when subjected to earthquake ground motions has been presented. The proposed procedure permits the estimation of both global and local inelastic displacement demands from elastic demands through the use of inelastic displacement ratios. An analytical expression to compute the ratio of inelastic to elastic displacements is proposed as a function of the displacement ductility ratio and the ratio between the period of the structure and the predominant period of the ground motion. The proposed expression gives good estimates of mean inelastic displacement ratios.

The procedure is tested by comparing maximum computed inelastic roof displacement demands and inelastic interstory drift demands with those computed with detailed nonlinear time history analyses of three reinforced concrete moment- resisting frame buildings. Results indicate that the procedure produces very good estimates of elastic demands of MDOF systems. For MDOF systems undergoing strong inelastic displacement demands the procedure yields good estimates of the maximum roof displacement and small underestimations of maximum interstory drift demands.

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