Earthquake Engineering, Tenth World Conference © 1992 Balkema, Rotterdam. ISBN 90 5410 060 5

Nonlinear response of buildings, a parametric study

E. F. Cruz
The Catholic University of Chile, Chile

S. Cominetti
Universidad de Santiago, Santiago, Chile

ABSTRACT: Simple three-dimensional models of building structures are subjected to an ensemble of real earthquake motions. The models cover a range of building characteristics changing the fundamental period and the ratio of the first rotational and translational natural frequencies. The nonlinear response is computed for different levels of inelastic behavior (μ parameter) and the distribution of inelastic behavior throughout the structure is examined in terms of rotation ductility ratios. The averages over the ensemble of records of the nonlinear analyses results are compared to response spectrum analyses (RSA) results for the average spectrum looking at the ratio of the nonlinear to the RSA response. For the response quantities considered these factors show similar behavior, they are strongly dependent on the fundamental period and on μ. The dispersion in the results increases as the importance of torsional effects increases.

1 INTRODUCTION

The nonlinear behavior of planar structures subjected to severe earthquake ground motions has been studied over the past years by many authors; an extensive literature survey can be found in Cruz and Cominetti (1990b). In the last few years these studies have been extended to three dimensional one story structures (Goel and Chopra 1990) and also to some special clases of building models (Chandler and Basset 1991).

Most of the previous work has been devoted to identifying the controlling parameters of the behavior, and some of it to developing simple methodologies to allow the estimation of the nonlinear response of the structure based on elastic analysis. The research effort reported here is directed towards the same general objective, but deals with the behavior of three-dimensional multi-story structures. The scope of the research has been limited to building type structures, with plane frame type resisting elements. The aim of this research work is to check the quality of the results obtained from the code type analysis procedures actually in use, where the earthquake actions for the different resisting elements in the structure are obtained from an elastic response spectrum analysis (RSA), and then reduced by a response modification factor, that in most cases is independent of the fundamental period of the structure, but depends on the overall structural characteristics and on the material properties (ICBO 1990, INN 1989). For that purpose the results from the nonlinear time history analysis of several simple models averaged over a set of eight different earthquake records are compared to the results from standard RSA of the models considering the average spectrum of the ensemble of records.

2 MODELS AND EARTHQUAKE MOTIONS

The structural system model considered is that of a five story building, regular in height. A schematic of the structure configuration in plan is shown in Figure 1. The mass is considered lumped at the story levels, uniformly distributed over the floor diaphragm; which are considered to be rigid in their own plane, therefore only three degrees of freedom are used at each level: the displacements of the center of mass. This idealization had been used previously by Hejal and Chopra (1989) for the elastic analysis of this type of buildings. For each of the component frames (Figure 1) the ratio of beam to column stiffness is 0.125, typical of a case where frame action, the effects of joint rotations relative to that of floor displacements, is important in determining the lateral behavior of each frame (Cruz and Chopra 1986).

The lateral stiffnesses of the frames and the model static eccentricity are adjusted to obtain different values of the ratio of the lowest two natural frequencies corresponding to natural modes that are predominantly torsional and predominantly translational in the direction of the earthquake action respectively, $\Omega = \omega_\theta/\omega_y$. Three values of Ω are considered (2.0, 1.5, and 0.5), they are obtained changing the ratios of lateral stiffness for the frames between 1.0 and 0.5 and the static eccentricities between 0.1 and 0.25 of the plan dimension. To cover a wide range of structures the fundamental period of the model (translational) is varied between 0.25 and 2 sec. changing the stiffness properties of the frame elements.

The behavior of the different elements in the individual frames is modeled through a simple beam-column flexural element, that can only experience inelastic behavior at the ends (point hinge model). For the columns the effect of axial forces in the flexural strength is neglected. The moment-rotation curve is assumed to be bilinear with 10% of the original stiffness in the second branch. The strength provided at the element ends was computed as a fraction of the required strength as computed from elastic analysis (average over the ensemble of records). The columns were specified to have an over-strength of 25%. The fraction to use was determined using a reduction factor that was computed as $R=\sqrt{2\mu-1}$ where μ is defined as an overall ductility ratio and is arbitrarily given the values 2 and 4 to represent different levels of inelastic behavior in the structure. The same values are used for positive and negative moments for all the elements in the different frames.

Eight different earthquake records were used, the two horizontal components of the records obtained for the Central Chile earthquake of March 3, 1985 at four different sites in the vicinity of the epicenter: El Almendral (Valparaíso), Universidad F. Santa María (Valparaíso), Viña del Mar, and Llo-Lleo. After being corrected using a segmental parabolic base line correction procedure, the individual records were normalized to have 0.4g peak ground acceleration. The average and the average plus and minus one standard deviation over the set of eight records of the pseudo-velocity elastic response spectrum for 5% damping are shown in Figure 2.

3 METHODS OF ANALYSIS

The nonlinear analysis of the models subjected to the earthquake motions was done using the computer program DRAIN-TABS (Guendelman and Powell 1977). The program computes the time history response of the structural system by direct numerical integration of the differential equations of motion, using the Newmark constant acceleration integration scheme. The time step for the integration was determined after checking the accuracy of the results through a sensitivity analysis. The damping matrix of the system was defined as a linear combination of the mass and stiffness matrices, so as to obtain 5% damping for the first two natural vibration modes. The maximum of the response quantities of interest are averaged over the ensemble of records.

Standard response spectrum analysis (RSA) was used to compute the response of the different models for the average spectrum of the 8 records considered. Damping was considered to be 5% of critical for all the natural vibration modes. The estimate of the maximum response for each of the effects of interest was obtained from the superposition of the individual modes maximum values using the CQC superposition formula (Der Kiureghian 1981).

4 RESULTS OBTAINED

For the model buildings and the ground motions described above the response was studied considering several different quantities. To look at the overall behavior of the structure the displacements of the diaphragm at the floor levels were considered. To look at the local effects the member end rotations and moments were considered. The amount of inelastic behavior in the different elements of the structure was studied computing ductility ratios μ_m and μ_a, based on maximum inelastic rotation and accumulated inelastic rotation respectively (Cruz and Cominetti 1990a). Samples of typical results are shown in Table 1, for the frame perpendicular to earthquake action (Frame U) and one parallel to it (Frame V) in a building model with frequency ratio $\Omega = 2$.

The effect of the frequency ratio Ω on the response of the structure is examined based on results like those shown in Figure 3. Similar results are obtained for the other overall response quantities considered. The influence of the fundamental period of the structure can be studied from data such as that shown in Figure 4.

The average results obtained from the nonlinear analysis are compared to the results from RSA using the average spectrum through the computation of ratios of the RSA results to the average over the eight records of the nonlinear analysis results. The ratio is computed for different response quantities, to represent the overall behavior (story and frame lateral displacements) and the local behavior (member end rotations and moments). Sample results are shown in Figure 5 for the displacements of the three top stories.

Table 1. Ductilities at the base of the first story column. Average over 8 records. $\Omega = 2$.

	Frame U			
Period	$\mu=2$		$\mu=4$	
(sec.)	+	-	+	-
	Maximum Rotation Ductility			
0.25	1.30	1.26	1.85	1.79
0.75	0.89	1.02	1.37	1.63
1.60	0.59	0.64	0.83	1.88
2.00	1.21	1.01	1.54	1.45
	Accumulated Rotation Ductility			
0.25	1.66	1.67	4.72	4.52
0.75	0.89	1.17	4.17	4.36
1.60	0.59	0.64	0.83	1.97
2.00	1.47	1.31	2.73	2.80
	Frame V			
Period	$\mu=2$		$\mu=4$	
(sec.)	+	-	+	-
	Maximum Rotation Ductility			
0.25	1.54	1.53	4.63	2.94
0.75	1.10	1.17	1.83	1.97
1.60	1.09	0.85	1.57	1.37
2.00	1.10	1.14	1.64	1.86
	Accumulated Rotation Ductility			
0.25	2.71	2.77	79.23	78.73
0.75	2.79	2.77	9.84	9.91
1.60	1.16	0.85	2.63	2.29
2.00	1.25	1.29	2.84	2.98

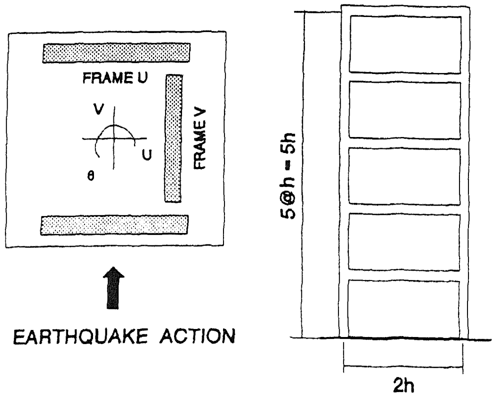

Figure 1. Schematic of plan configuration and *component frames of structural system model.*

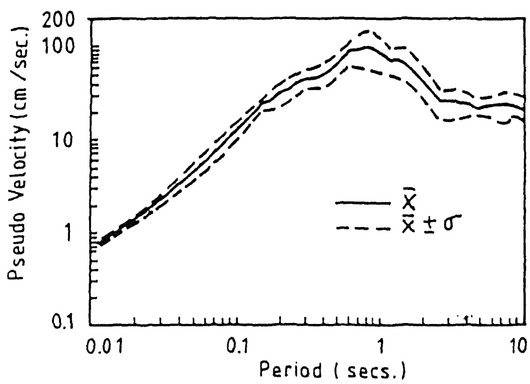

Figure 2. Pseudo-velocity response spectrum, average over 8 records of the Central Chile earthquake of March 3, 1985 (adapted from Cruz and Cominetti 1990a).

5 CONCLUSIONS

Based on the results obtained, of which only a very small part have been shown, the following conclusions can be stated:

1. Among the many parameters in the nonlinear response of the buildings, the expected level of inelastic behavior (represented by the overall ductility μ) and the fundamental period are the ones that most strongly affect the response.

2. The ratios between the RSA results and the nonlinear results show a rather clear tendency, for almost all cases considered, that can probably be approximated through bilinear relations, as a function of the fundamental period and having μ as a parameter. These results are consistent with what has been observed for plane structures, but the dispersion in them is definitely larger.

3. The influence of the coupling between torsional and translation motion in the structures (represented through the frequency ratio Ω) is most apparent in the behavior of the frame perpendicular to the direction of earthquake action. As the importance of the torsional effects increases the dispersion in the results also increases, thus making the use of average results somewhat unreliable.

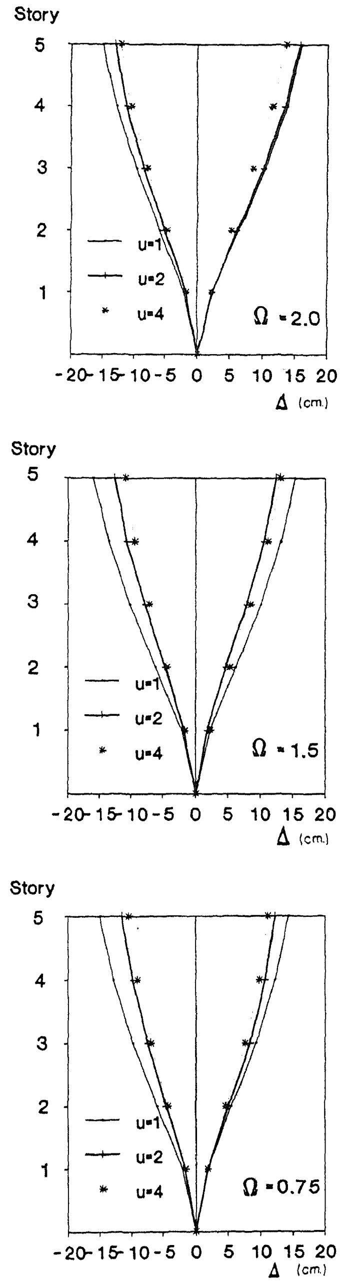

Figure 3. Importance of torsional coupling in the lateral displacements of FRAME V. Fundamental period T = 1.6 sec.

The results that have been generated in this study should provide a rational basis for discussing the limits of applicability of some of the provisions now in effect in building codes, especially those dealing with Response Modification Factors.

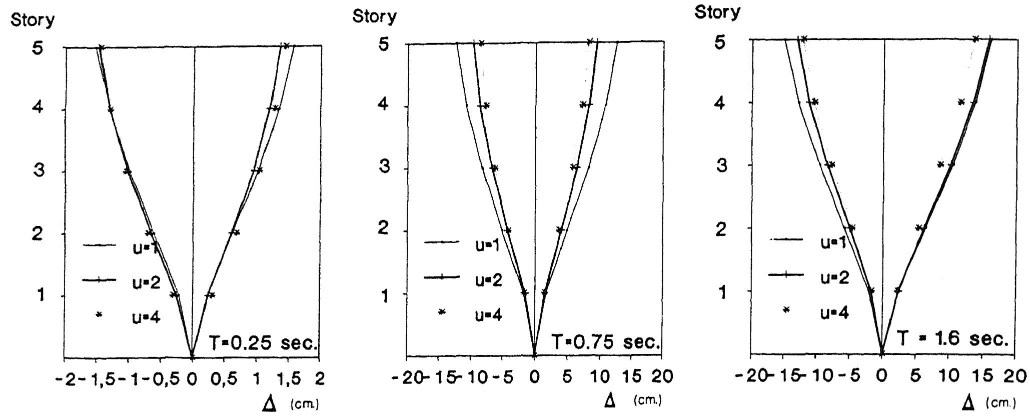

Figure 4. Influence of the fundamental period in the lateral displacements of FRAME V. $\Omega = 2$.

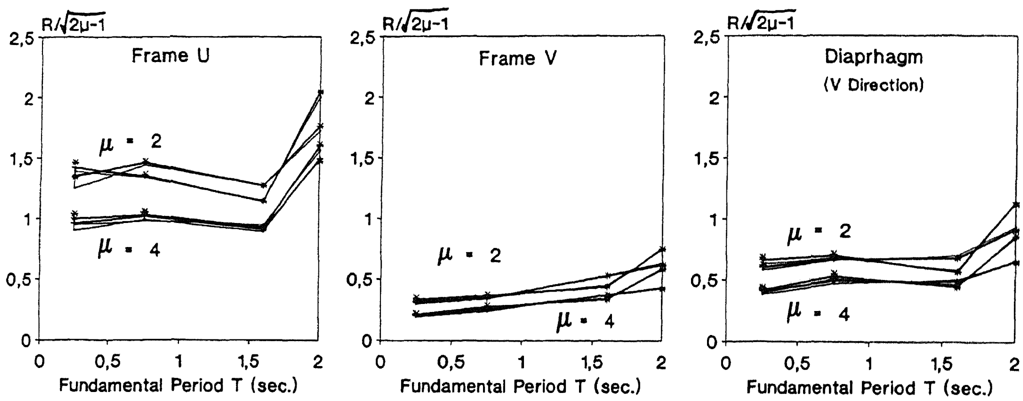

Figure 5. Normalized response modification factors for lateral displacements. $\Omega = 2$.

ACKNOWLEDGMENTS

Funding has been received from FONDECYT, the Chile National Council for the Development of Science and Technology (Grant No. 764-91).

REFERENCES

Chandler, A.M. & R.H. Basset 1991. Coupled lateral torsional behavior of frame structures under earthquake loading. *Earthquake eng. struct. dyn.* 20:61-85.

Cruz, E.F. & A.K. Chopra 1986. Elastic earthquake re sponse of building frames. *J. Struct. eng.* 112:443-459.

Cruz, E. & S. Cominetti 1990a. Estimation of inelastic response of buildings based on elastic response spectrum analysis. *Proc. 4th U.S. Natl. Conf. Earthquake Eng.* 2:87-96. Palm Springs: EERI.

Cruz, E. & S. Cominetti 1990b. Nonlinear analysis of buildings under earthquake excitation. *Report DIE 90-12, Structural Eng. Dept.* (In Spanish). Santiago: The Catholic University of Chile.

Der Kiureghian, A. 1981. A response spectrum method for random vibration analysis of MDOF systems. *Earthquake eng. struct. dyn.* 9:419-435.

Goel, R. & A.K. Chopra 1990. Inelastic seismic response of one-storey asymmetrical plan systems: effect of stiffness and strength distribution. *Earthquake eng. struct. dyn.* 19:949-970.

Guendelman, R. & G.H. Powell 1977. DRAIN-TABS: a computer program for inelastic earthquake response of three-dimensional buildings. *UCB/EERC Report No. 77-08.* Berkeley: University of California.

Hejal, R. & A.K. Chopra 1989. Earthquake analysis of a class of torsionally-coupled buildings. *Earthquake eng. struct. dyn.* 18:305-323.

ICBO, International Conference of Building Officials 1990. *Uniform Building Code.* Whittier: ICBO.

INN, Instituto Nacional de Normalización 1989. *NCH433cR-89: Seismic design of buildings* (In Spanish). Santiago: INN.