SEISMIC RESPONSE SPECTRA FOR NONLINEAR STRUCTURES

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SUMMARY

The objective of this paper is to determine the magnitude of the errors introduced by the use of the modal superposition method and response spectra in inelastic seismic design. This error is evaluated by analyzing some simple "shear building" structures using an exact method and comparing the obtained results with the solution obtained by modal superposition and the use of response spectra in the inelastic range. This comparison indicates that, for systems exhibiting inelastic behavior, displacement errors of about 50% may be expected when response spectra and modal superposition are used in seismic design of buildings.

INTRODUCTION

In recent years the response spectrum method has been widely accepted as an efficient procedure for the seismic analysis and design of structures (Blume, 1961). It is well known that in order to use this method it is necessary to solve an eigenvalue problem to obtain the natural frequencies and modal shapes of the structure. The maximum response for each mode is then obtained from charts prepared for a specific seismic excitation. Finally, the total response is computed as a suitable combination, such as the square root of the sum of squares of maximum modal contributions.

The modal analysis method is based on the assumption that the structure is linearly elastic and that it remains linerally elastic during the duration of the seismic excitation; i.e., the structure suffers no permanent deformation. For an earthquake of moderate intensity, it is reasonable to make this assumption for a well-designed structure. However, for strong or very strong motions this is not a realistic assumption even for well-designed structures. While structures can be designed to resist severe earthquakes, it is not feasible economically to design all buildings to withstand elastically to earthquake of greatest foreseeable intensity.

In order to design structures for stress levels beyond the linear elastic range, the response spectrum method has been extended to include the inelastic stress range (Newmark, 1973). Unfortunately, the use of this method in the inelastic range in conjunction with modal analysis cannot be justified analytically. Though charts for inelastic response spectra are available and the method is used in practice, the real response of the structure remains uncertain since the method is not valid in the inelastic range.

This paper presents the results of analysis of some simple structural frames to ascertain the discrepancy which results from the incorrect use

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of modal analysis for non-linear systems. The analysis is undertaken by solving the corresponding differential equations of motion using a step-by-step method of integration and comparing the results with the response obtained using the spectrum method. The excitation produced by the ground motion of the well-known El Centro earthquake of 1940 is applied to several structures in which the ductility is varied as a parameter. The maximum displacements determined by using the response spectrum technique is compared with the results obtained from the time-history response.

COMPARISON OF TIME-HISTORY AND RESPONSE SPECTRUM RESULTS

The maximum horizontal displacements of several structural frames are obtained using modal superposition method and spectrum charts. Table 1 shows the results obtained for a two-story shear building with natural periods T_1 = 1.0 sec. and T_2 = 0.384 sec. This table includes results for cases where the ductility ratio varied between one and about five and where damping the ratio varied from zero up to 20% of the critical damping for each mode. The maximum displacements are given in this table for the modal superposition method with both the El Centro 1940 response spectrum and the design response spectrum chart for the inelastic range as recommended by Newmark (1973). The maximum displacements for a five-story shear building obtained using modal analysis and spectrum charts are compared with corresponding maximum displacements obtained from time-history analysis in Fig. 1 where the maximum amplitude ratios are plotted as function of the ductility ratio without regard to damping coefficient or story level.

The results of this study appear to indicate that the use of the superposition method of analysis with the actual response spectrum for the seismic motion results in errors of about $\pm$ 50% of the true response value. Higher discrepancies are observed, on the order of 100% when design earthquake charts for response spectra are used in the analysis.

CONCLUSIONS

The use of modal analysis and response spectra for analysis of inelastic behavior although it cannot be justified theoretically, is nevertheless a relatively simple and practicable method of seismic design. Results of application of this analysis to some simple structural frames, presented in this paper, indicate that displacement discrepancies between the "exact" solution and the spectrum solutions are on the order of 50% for ductility ratios up to five. Considering the uncertainties inherent in seismic design which requires the prediction of future ground motions, it could be concluded that these discrepancies can be in some cases tolerated. Further study of this problem is recommended before a final judgment on acceptability of response spectrum method in the inelastic range is made.

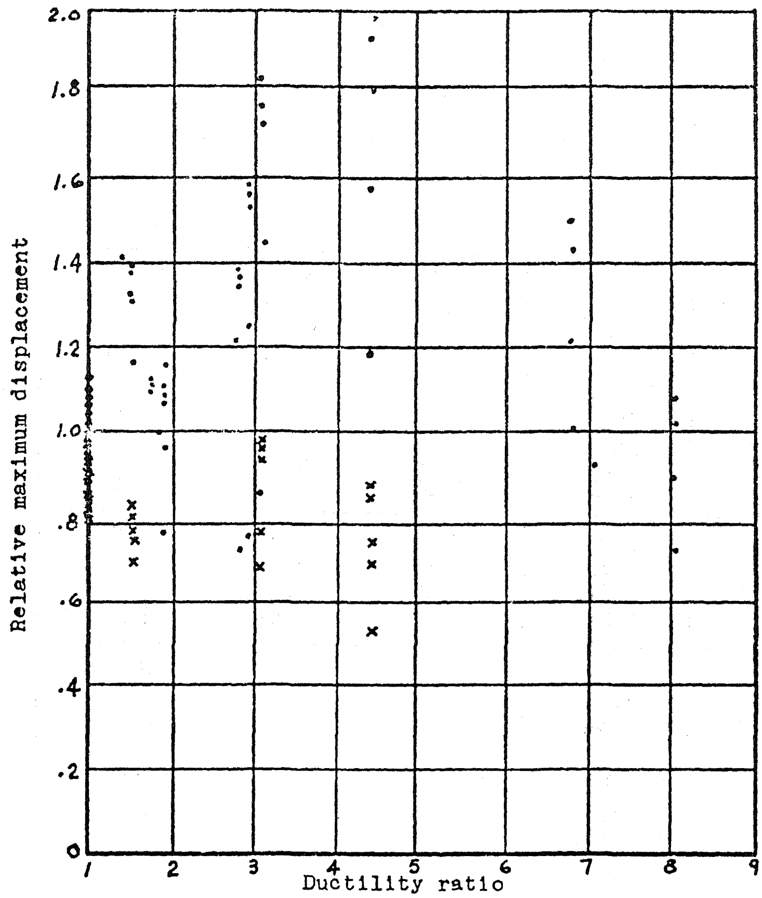

Fig. 1 Maximum displacements for a five-story shear building calculated using response spectra relative to time-history solution for El Centro earthquake. (X using El Centro response spectra, • using consolidated earthquake response spectra)

Table 1. Maximum Horizontal Displacements on the Second Floor of a Two-Story Shear Building

Damping ratio ξ	Ductility ratio μ	Maximum horizontal displacement (in)		
		Time History	El Centro Spectrum	Design Spectrum
0%	1.00	9.16	9.96	11.70
	1.21	9.07	9.61	11.70
	2.16	8.33	7.22	11.30
	3.67	7.94	6.01	11.30
5%	1.00	5.91	5.27	5.85
	1.58	5.90	5.90	5.85
	1.92	4.64	4.60	5.85
	6.02	5.63	6.33	5.85
10%	1.00	4.11	3.87	3.88
	1.31	3.89	3.84	3.90
	2.34	3.90	4.38	3.90
	6.36	4.73	4.47	3.90
20%	1.00	2.53		3.32
	1.41	2.57		3.32
	2.14	2.26		3.32

REFERENCES

Blume, J. A., N. M. Newmark and L. H. Corning (1961), Design of Multi-Story Reinforced Concrete Buildings for Earthquake Motions, Portland Cement Association, Skokie, Illinois.

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