AN EVALUATION OF THE RESPONSE SPECTRUM METHOD FOR LATERAL ANALYSIS OF BUILDINGS

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SUMMARY

The ensemble average of the maximum response of a class of multistory buildings to simulated ground motions, computed by time history analysis (THA) and response spectrum analysis (RSA) procedures, is plotted against the fundamental vibration period of the building in the form of response spectra. The dependence of the contributions of the higher vibration modes, and of the errors in the RSA results, on the fundamental vibration period and on the joint rotation index ρ, a measure of the relative beam to column stiffness of the building, is discussed.

INTRODUCTION

In most practical analyses of multistory buildings, the maximum earthquake response of a structure is determined directly from the response or the design spectrum. Furthermore, most building code specifications for earthquake forces are based on simplifications of the response spectrum method of analysis. In order to develop better simplified analysis procedures suitable for building codes, it is necessary to evaluate the accuracy of the response spectrum estimates of maximum response and to better understand the contributions of the various vibration modes in the response. This paper reports on a small part of a National Science Foundation sponsored research project designed to fill this need; it is an extension of Ref. 1.

SYSTEMS, GROUND MOTIONS, AND ANALYSIS PROCEDURES

Systems

The systems analyzed are idealized as single-bay, five-story moment-resisting plane frames with constant story height = h, and bay width = 2h. All the beams have the same stiffness I_b and the column stiffness I_c does not vary with height. The structure is idealized as a lumped mass system with the same mass m at all the floor levels. The damping ratio for all the natural modes of vibration is assumed to be five percent. Only two additional parameters are needed to completely define the system: the first mode period T_1 and the joint rotation index ρ (Ref. 2). For the selected class of building frames $\rho = I_b/4I_c$. By varying ρ the complete range of behavior of the frame can be covered, from the bending beam ($\rho = 0$) to the shear beam ($\rho = \infty$). Intermediate values of ρ represent frames with both beams and columns undergoing flexural deformations.

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Ground Motions

Eight simulated ground motions were generated as samples of a filtered stationary Gaussian white noise amplified by a time dependent intensity function. The average of the response spectra of these eight ground motions for five percent damping is presented on Fig. 1 together with the ensemble averages of the maximum ground acceleration, velocity, and displacement.

Analysis Procedures

Standard procedures were employed for both the time-history analysis (THA) and the response spectrum analysis (RSA) of the dynamic response of the idealized frame to the simulated ground motions. The THA was carried out by the mode superposition method. The maximum of each of the response quantities of interest during each simulated motion was determined. The ensemble average of the maximum response was obtained by averaging the maximum value corresponding to each of the eight simulated ground motions. In the RSA the maximum value of each of the response quantities of interest was estimated as the square-root-of-the-sum-of-the-squares (SRSS) combination of the individual modal maxima, computed directly from the average response spectrum of Fig. 1. The SRSS combination rule is adequate because the idealized frame has well spaced vibration frequencies.

PRESENTATION AND DISCUSSION OF RESULTS

The ensemble average of the maximum response, computed by including the contribution of all five vibration modes in the time-history analysis (THA) and in the response spectrum analysis (RSA) procedures, is plotted against the fundamental vibration period of the building in the form of response spectra; also included in these plots is the maximum response due only to the fundamental vibration mode, which is obviously identical whether computed by THA or RSA procedures. Such plots are presented in Figs. 2-7 for three values of $\rho = 0$, 0.125, and ∞ and six response quantities: top floor displacement u_5, base shear V_o. base overturning moment M_o, the largest moment M_b among all the beams, the largest moment M_c among all the columns, and the largest axial force P_c among all the columns. The response quantities are presented in dimensionless form as defined in Figs. 2-7, where $\bar{u}_g$ and $\bar{a}_g$ are the ensemble averages of the maximum ground displacement and ground acceleration respectively; W_1 and h_1 are the effective weight and effective height for the first vibration mode of the building. The normalization factors for V_o and M_o are the base shear and moment for a rigid single-degree-of-freedom system with lumped weight W_1 and height h_1.

The response contributions of the vibration modes higher than the fundamental mode increase, and apparently as a result the differences in THA and RSA results increase, with increasing fundamental vibration period T_1. Because, for a fixed ρ, the modes shapes and ratios of vibration frequencies do not change with T_1, the increased contribution of the higher modes is due only to the relative values of the response spectrum ordinates, which in turn depend on the spacing of the vibration periods and on the shape of the response spectrum. For the selected spectrum, as the fundamental vibration period increases the ordinate for a higher vibration mode generally increases relative to that for the fundamental mode, resulting in increased response contributions of the higher vibration modes and increased errors in the RSA results.

The response contributions of the higher vibration modes increase, and consequently the differences in THA and RSA results increase, with decreasing value of the joint rotation index ρ. A change in ρ affects the vibration modes shapes as well as the ratios of vibration frequencies. These two effects can be interpreted as separate, because the change in mode shapes affects the distribution of forces and displacements while the change in frequency ratios affects the relative importance of the dynamic amplification factor for the different modes. As ρ decreases the effective weight for the first mode tends to decrease and correspondingly the effective weights for the higher modes, especially for the second mode, tend to increase. At the same time the frequency ratios increase, spreading the frequencies over a wider portion of the spectrum, thus increasing the effects of the spectrum shape discussed above. Both of these factors contribute to increased response due to the higher vibration modes.

While the errors in the RSA results depend on the response quantity they are all below five percent for structures with fundamental vibration period less than four seconds. Among the overall response quantities the largest errors occur in the base shear values, with much smaller errors in the base overturning moment, and almost no errors in the top displacement. Among the local response quantities the largest errors occur in the column moments, while the errors in the beam moments and column axial forces are very similar; but these errors are all smaller than those in the base shear.

In addition to the already discussed trends in the results, the base shear, and to a lesser degree the base overturning moment, show some discrepancies between the RSA and the THA results for very short periods (Figs. 3 and 4), with the errors increasing as T_1 decreases in this range. The individual modal responses of a short period structure are essentially all in phase, resulting in the combined response being close to the sum of absolute values of modal responses and larger than the SRSS estimate which is close to the first mode response.

Although the results presented are for a one-bay five-story frame with uniform distribution of mass and stiffness over height subjected to a small set of simulated ground motions, the trends observed can be explained in terms of both basic principles of static and dynamic analysis and the characteristics of the model and the average spectrum of the ground motions. Therefore, the same trends are expected to be found in the responses of a much wider range of structures, with different number of stories and with distributions of mass and stiffness that change gradually over the height, under the action of excitations with spectra similar to the one used here.

In order to provide a complete evaluation of the RSA the results presented here need to be extended. The areas in which further research is planned include: effects of the heightwise distribution of mass and stiffness, and effects of the model frame characteristics (number of stories, number of bays, and bay-width to story-height ratio).

REFERENCES

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2) Blume, J. A., "Dynamic Characteristics of Multi-story Buildings," Journal of the Structural Division, ASCE, Vol 94, No ST2, Feb. 1968, pp. 337-402

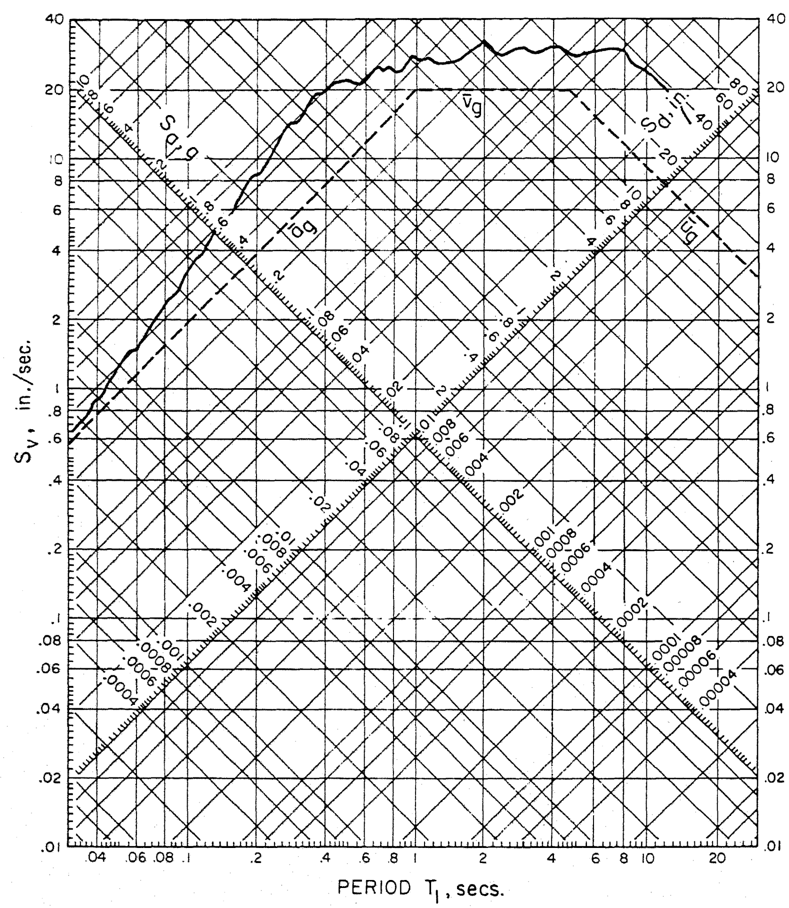

Fig. 1 Average Response Spectrum (5% damping) for Eight Simulated Motions.

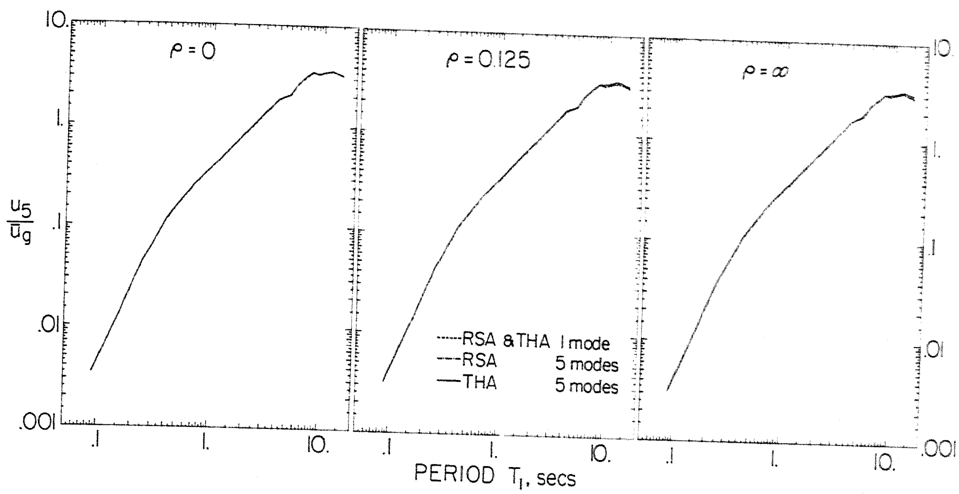

Fig. 2 Maximum Top Story Displacement.

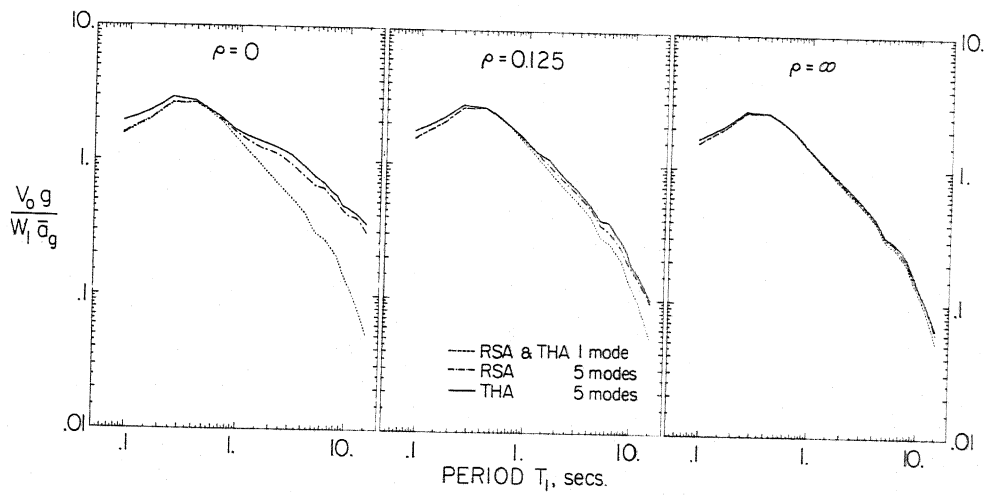

Fig. 3. Maximum Base Shear.

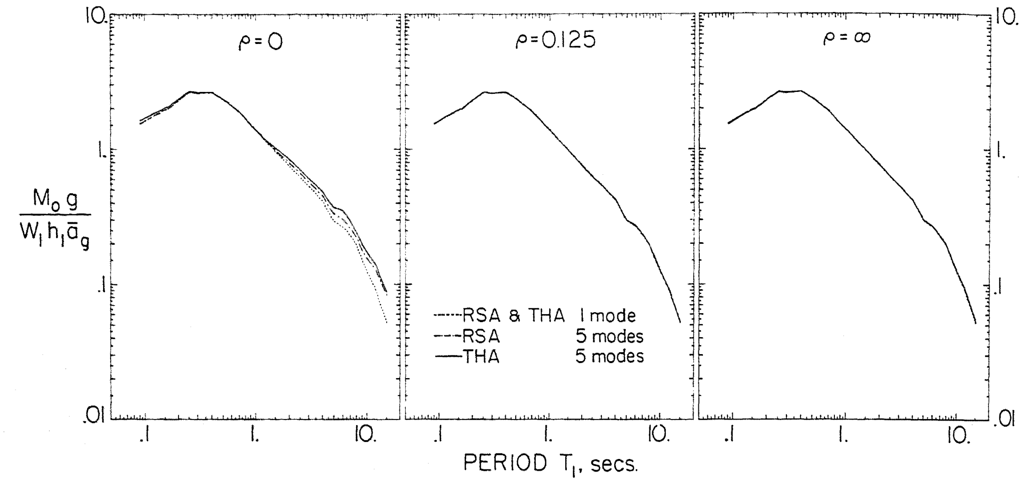

Fig. 4 Maximum Base Overturning Moment.

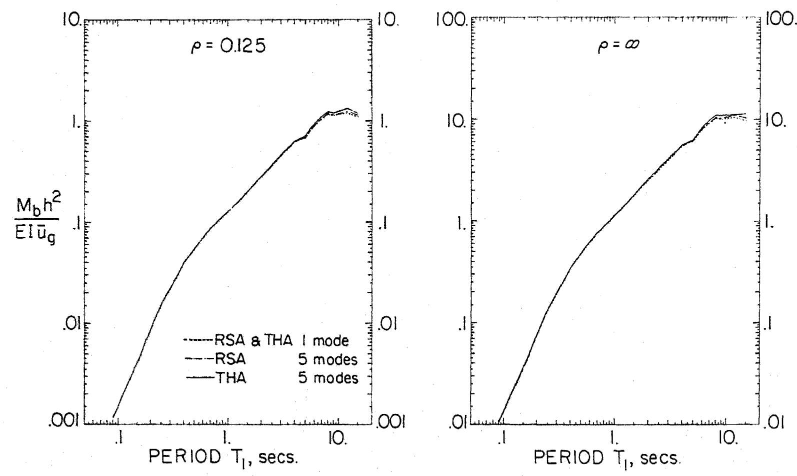

Fig. 5 Maximum Beam Moment.

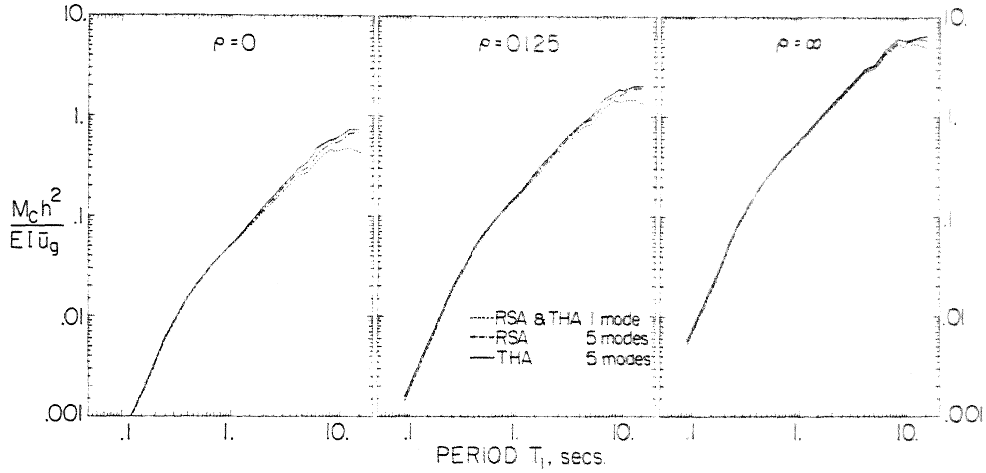

Fig. 6 Maximum Column Moment.

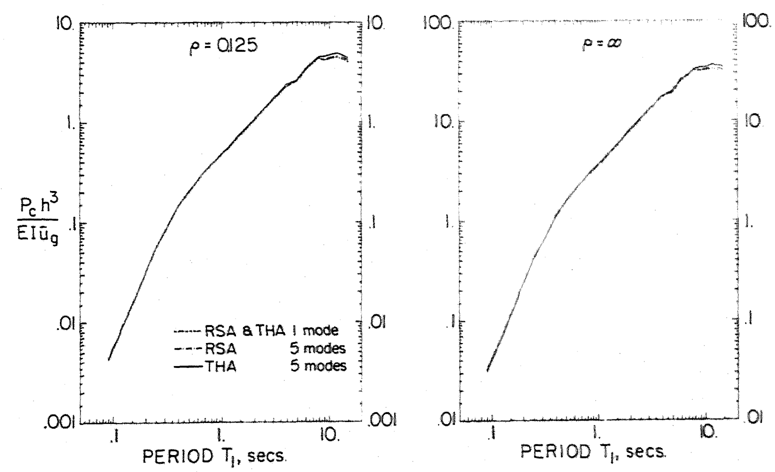

Fig. 7 Maximum Column Axial Force.