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EVALUATION OF AN IMPROVED CODE-TYPE PROCEDURE FOR PRELIMINARY DESIGN

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SUMMARY

An improved code-type procedure for earthquake analysis of buildings is presented. The results obtained from applying the procedure to several building models are compared to response spectrum analysis results. The errors are found to be dependent on overall building characteristics, especially the fundamental period and the beam-to-column stiffness ratio, also to be small enough for the results to be used for preliminary design over a wide range of buildings with different characteristics. This is provided that buildings have distributions of mass and stiffness over the height that do not change abruptly.

INTRODUCTION

The equivalent lateral forces analysis procedures specified in building codes (Refs. 1,2,3) are intended to provide an initial estimate of the earthquake forces without a preliminary design of the building. It was demonstrated (Ref. 4) that earthquake forces are especially affected by two overall building parameters, fundamental vibration period T_1 and beam-to-column stiffness ratio ρ; but the effects of these parameters are not properly recognized in building codes. Based on these results a procedure to estimate the earthquake forces for the preliminary design of buildings, which recognizes the important influence of these parameters on building response was developed (Ref. 5).

An evaluation of the quality of the results obtained from applying the improved code-type procedure to several different model structures is reported here. The ranges of the basic properties of the structures for which the results from the procedure are adequate to be used in preliminary design are identified.

IMPROVED CODE-TYPE ANALYSIS PROCEDURE

The basic idea behind the improved code-type analysis (ICA) procedure is to compute the response of the structure considering the contributions of the first two natural modes of vibration. The total base shear is computed as the product of the first mode effective weight W_1^* and a seismic coefficient C which is obtained from the pseudo-acceleration design spectrum through a simple modification that consists in raising the decaying portion of the spectrum in varying amounts that depend on the overall characteristics of the structure.

The modifications to this spectrum are intended to account for the contributions to the base shear of the modes of vibration higher than the first one. These higher-mode contributions depend on building properties, the most significant of which are fundamental vibration period T_1 and stiffness ratio ρ. This parameter was defined (Ref. 6) as the ratio of the sum of the stiffnesses of all the beams at mid-height story of the frame to the summation of the stiffnesses of all the columns at the same story. The design spectrum (Sa/g) is modified as shown in Fig. 1. It is left unchanged in the acceleration-controlled region, but is modified in the velocity and displacement-controlled regions. The exponents β_v and β_d depend on building properties, especially on the stiffness ratio ρ; their values for the 5 different frame models of Fig. 2 can be found in (Ref. 4).

The first mode effective weight W_1^* can be computed from the standard equation (Ref. 7) based on estimates of the height-wise distribution of building weight and of the fundamental mode shape. Alternatively, it can be estimated from Fig. 3, where it is shown as a function of ρ for the 5 frame cases shown in Fig. 2 in terms of W, the total weight of the building.

It has been demonstrated (Ref. 8) that, over a useful range of fundamental vibration periods, the earthquake response of building frames can be satisfactorily estimated by response spectrum analysis considering the contributions of only the first two modes of vibration; even the first mode alone is usually sufficient in the acceleration-controlled region of the spectrum. Thus if we could separate the total base shear into the first mode contribution and ascribe the remainder to the second mode it would be possible to distribute each modal base shear over the building height in accordance with the corresponding mode shape. This is an indirect, approximate way to determine the response in the fundamental and second modes of vibration. The total response can then be obtained by appropriately combining the modal responses.

The first mode base shear V_{01} can be obtained as the product of W_1^* and Sa_1, the ordinate of the pseudo-acceleration design spectrum. The remainder of the base shear, obtained under the assumption that the total base shear is best given by a SRSS combination of modal values, $V_{02}^2 = V_0^2 - V_{01}^2$, is treated as an estimate of the base shear due to the second vibration mode. Having estimated the base shears due to the first two modes of vibration, the equivalent lateral forces in each mode can be determined from standard equations. The remainder of the analysis is the same as the standard response spectrum analysis (Ref. 7).

What remains to be determined are the periods and the shapes of the first two modes of vibration. These vibration properties can not be computed exactly without the building having been designed. An estimate of the fundamental vibration period is required in most of the existing building codes. For this purpose, empirical formulas have been developed (Ref. 1) these are based on only a general description of the building type --e.g. steel or concrete moment frame, shear wall system, braced frame, etc.-- and overall dimensions such as height and plan size. Such formulas may be employed in this ICA procedure, but it should be recognized that they often lead to significantly inaccurate values.

It is recommended that the first two mode shapes be approximated by

$$\phi_{j1} = (h_j/H)^{\delta} \quad \text{and} \quad \phi_{j2} = (h_j/h_0)(1 - h_j/h_0),\ j = 1,2,\ \ldots\ N \qquad (1)$$

respectively, where h_j is the height of the jth floor above the base, H is the total height of the building, and h_0 is the height of the node (point of zero displacement) above the base. As shown in Figs. 4 and 5 the exponent δ and the height h_0 depend on the building properties including the number of stories, height-wise variation of mass and stiffness, but perhaps most significantly on the beam-to-column stiffness ratio ρ. Because δ and h_0 vary gradually with ρ they can be estimated to a useful degree of accuracy from the data presented. Although these approximate shapes are not always excellent, they are obviously better than the mode shapes independent of implied in building codes. Similarly, the ratio T_2/T_1, needed to compute displacements in the second mode, can be obtained from the data shown in Fig. 6.

EVALUATION OF APPROXIMATE RESULTS QUALITY

The analysis procedure used to generate the "exact" results to check the quality of the results obtained from the ICA procedure is the standard response spectrum analysis (RSA) (Ref. 7). The maximum modal responses obtained for the pseudo-acceleration design spectrum in Fig. 1 (Sa/g) are combined using SRSS.

The results obtained using the ICA procedure are compared to the results obtained from standard RSA for the 5 different plane frame building models of Fig. 2. The frames are idealized as single-bay, moment-resisting plane frames with constant story height = h, and bay width = 2h. Only flexural deformations are considered in the members which are assumed to be prismatic. The modulus of elasticity E is the same for all members but the moments of inertia of beams I_b and columns I_c --same for both columns in any story-- may vary over the height, as in cases 3 to 5 (Fig. 2), with the ratio of the two same in all stories. The mass of the structure is assumed to be concentrated at the floor levels and the rotational inertia is neglected. The damping ratio for all the natural modes of vibration is assumed to be 5 percent.

<u>Overall Responses</u> The errors in the ICA results for the base shear V_0 and the base overturning moment M_0 are shown in Figs. 7 and 8 as a percentage of the RSA results for the three ρ cases considered and the 5 frame cases being used. For V_0 errors are seen to be within 10% for all but frame case 5 when T_1 is below 3.75 secs. Errors are larger for the smaller values of ρ and they tend to increase as T_1 increases. For M_0 the errors are much smaller than for V_0 and they do not exceed 10%, except for frame case 5 for T_1 greater than 5 secs. and $\rho = 0$. The errors in the ICA results are negative for most of the cases considered thus indicating that the ICA procedure results tend to slightly underestimate the RSA results for the base shear and for the base overturning moment.

<u>Distributions over the Height</u> The distributions of story shears over the height of the frames obtained from the ICA procedure and the RSA procedure are very close for the 5 frame cases considered and the 3 different values of ρ. Even for the long period cases (T_1 = 4.11 sec.) the ICA distribution closely follows the RSA distribution. In Fig. 9 results are shown for frame case 3, for 4 period cases selected as representative of the different parts of the spectrum and the 3 values of ρ considered. The results for the other frame cases are similar.

The errors in the ICA results are normally within 10% of the RSA results, except for a few cases where the errors are somewhat larger. These larger errors occur mainly in the top stories where the absolute values of the story shears are small. The largest error is smaller than 35%. Equivalent results for the story overturning moments are shown in Fig. 10, where excellent agreement between the results from ICA and RSA is found. This is not unexpected as it has been shown (Ref. 8) that the distribution over the height of story overturning moments is far less sensitive to changes in ρ and the fundamental period T_1 than the story shears distribution because the importance of the contributions of the higher modes to these response quantities is much smaller.

In Figs. 9 and 10 the distributions of story shear and story overturning moments corresponding to the UBC (Ref. 2) lateral forces distribution are also shown. For long period structures the errors in the ICA results are seen to be definitely smaller than those in the UBC distributions.

CONCLUSION

The ICA procedure to estimate the earthquake forces for the initial, preliminary design of buildings presented is able to recognize the important influence of those building properties and parameters that significantly affect its earthquake response, without requiring the computations inherent in standard dynamic analysis by the response spectrum method. It represents a major conceptual improvement over present building codes with very little increase in computational effort. The errors in the ICA procedure results, for the base shear and the base overturning moment and also for the distribution over the height of story shears and story overturning moments, are such that the procedure can be considered suitable for preliminary design of frame buildings with fundamental period up to about 3 seconds; provided they have distributions of mass and stiffness over the height that do not change abruptly. For all other cases the results should be an improvement over those obtained using actual codes lateral forces but will need refinement before they can be used for design.

ACKNOWLEDGEMENTS

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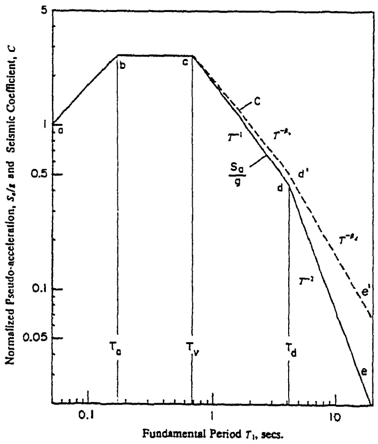

Fig. 1 Construction of C spectrum from Sa/g spectrum.

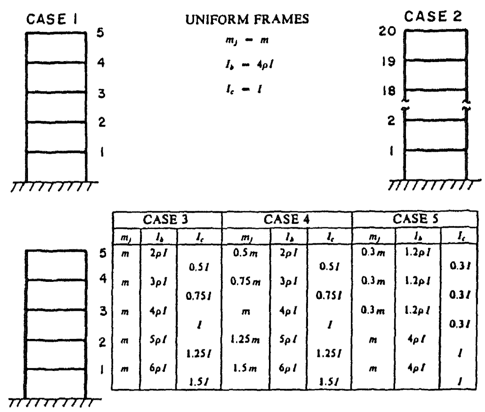

Fig. 2 Idealized building frames

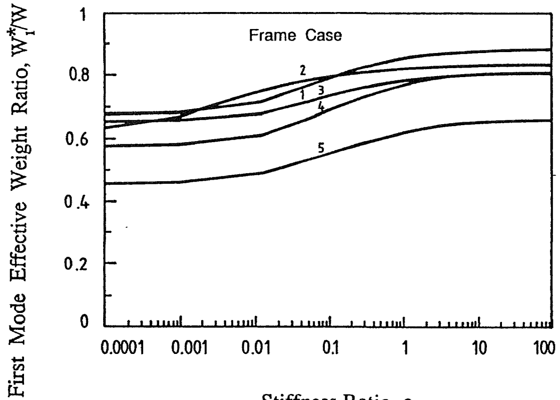

Fig. 3 Variation of first mode effective weight ratio to total weight with stiffness ratio ρ for five frame cases.

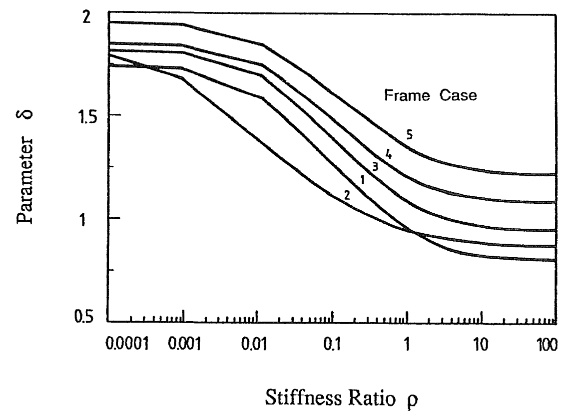

Fig. 4 Variation of parameter δ with stiffness ratio ρ for five frame cases.

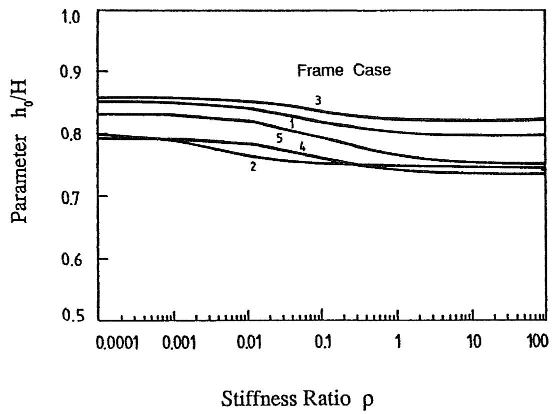

Fig. 5 Variation of parameter h_0 with stiffness ratio ρ for five frame cases.

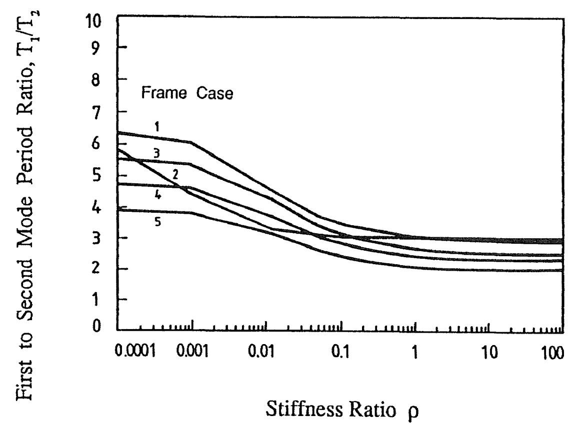

Fig. 6 Variation of the ratio of first mode to second mode period with stiffness ratio ρ for five frame cases.

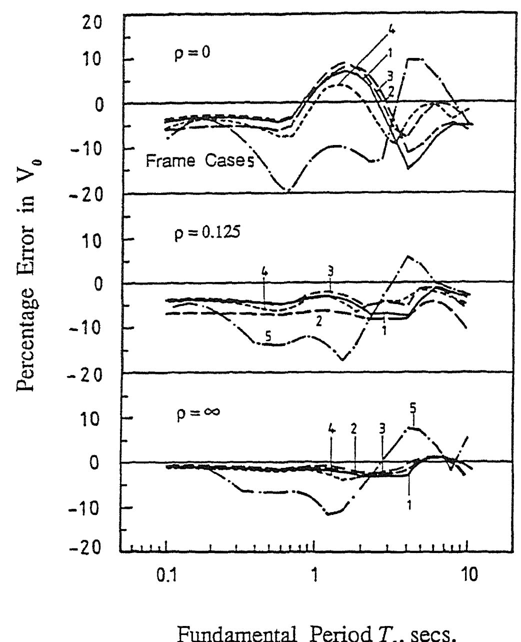

Fig. 7 Percentage error in base shear computed by ICA method, relative to RSA results, 5 frame cases.

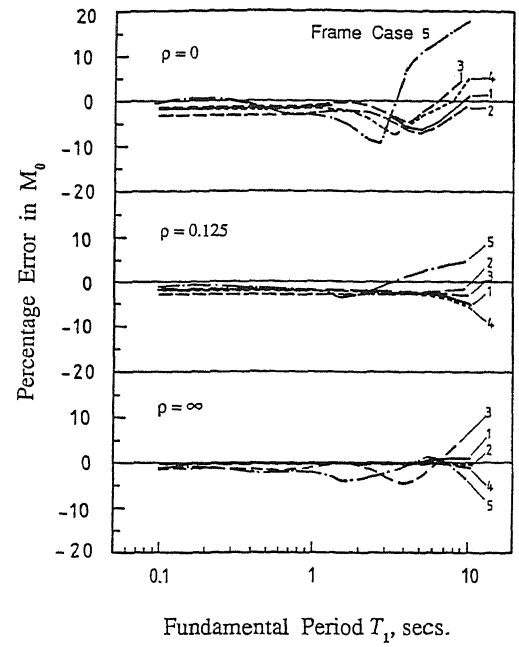

Fig. 8 Percentage error in base overturning moment computed by ICA method, relative to RSA results, 5 frame cases.

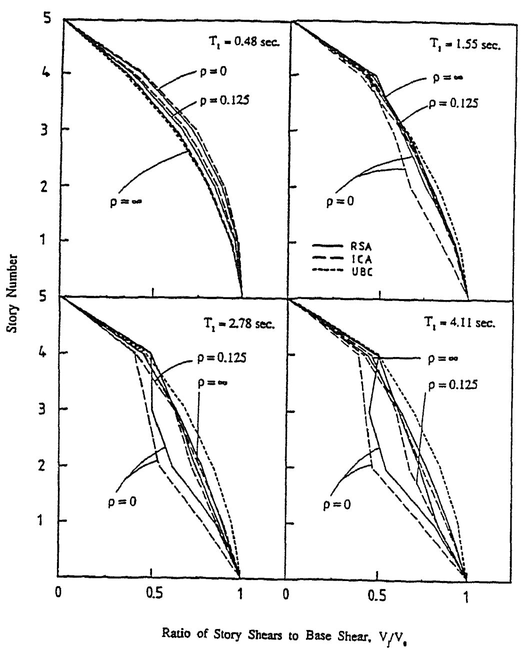

Fig. 9 Comparison of story shears distributions computed by RSA and ICA methods (Case 3).

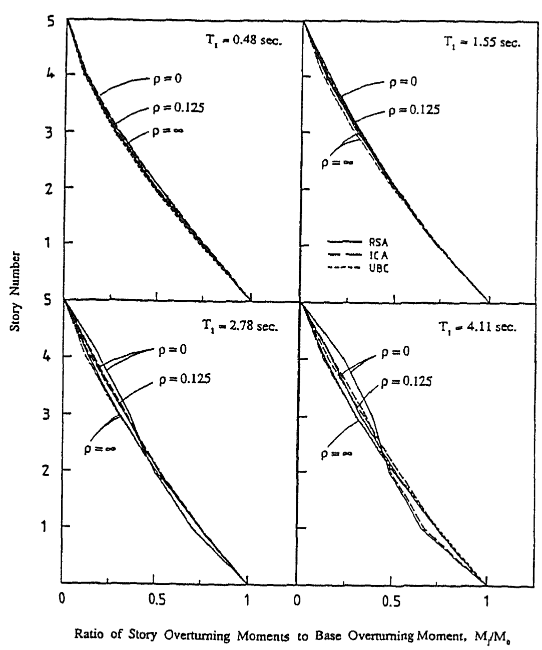

Fig. 10 Comparison of story overturning moment distributions computed by RSA and ICA methods (Case 3).