INELASTIC SEISMIC RESPONSE OF INSOLATED STRUCTURAL WALLS

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INTRODUCTION

Observations of building damage due to earthquakes over the last two decades have gradually led engineers to recognize the need for buildings which not only survive strong ground motions without collapse but survive these motions with the minimum of damage to both structural and nonstructural components. Thus, it is felt that in addition to the primary requirement of life safety, a requirement for damage control under strong ground motion be included in the performance criteria for buildings in seismic areas. The added requirement becomes particularly important for buildings such as hospitals and buildings housing power supply facilities, the continued operation of which is essential after an earthquake. Limiting damage to nonstructural components also becomes economically desirable in tall office and apartment buildings where such components make up from 60-80% of the total cost of the building. The superior performance of reinforced concrete multistory structures stiffened by properly proportioned structural walls (i.e., shear walls), particularly with respect to damage control, has focused attention on the need for more information on this type of structure.

The results reported here represent part of the data obtained during the first phase of an analytical investigation aimed at determining the force and deformation requirements in structural walls and wall systems when subjected to strong ground motions. The analytical study forms part of a combined analytical and experimental program undertaken at the Portland Cement Association under a grant from the National Science Foundation. A more extensive discussion of the results of the analytical investigation on isolated structural walls is given in Reference (1).

VARIABLES CONSIDERED

The dynamic inelastic analysis was undertaken within the framework of a parametric study. Among the parameters considered were fundamental period, yield level, post-yield stiffness ratio, stiffness and strength taper, rate of stiffness degradation under cyclic loading, degree of base fixity and ground motion intensity, duration and frequency characteristics. The results reported here are those relating particularly to the effects of the two major structural parameters, i.e., the initial fundamental period and yield level as well as the frequency characteristics of the ground motion.

The basic structure considered is a 20-story building consisting of a series of parallel walls having the same width as the building itself. This is shown in Fig. 1. A reference or base structure with a fundamental period of 1.4 sec. was first designed in accordance with current code provisions. Subsequent cases had only one parameter varied at a time, with the other structural and ground motion parameters held constant, due regard being given to the practical range of variation of each parameter.

Except where the duration of the ground motion was the parameter investigated, a duration of 10 seconds was used throughout the analysis. The intensity of the different accelerograms used as input to the dynamic analyses was normalized in terms of the 5% damped "spectrum intensity", here taken as the area under the 5% damped relative velocity response spectrum between ordinates representing 0.1 sec. and 3.0 sec. The spectrum intensity corresponding to the first 10 seconds of the N-S component of the 1940 El Centro record was used as the reference intensity.

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The dynamic analyses were carried out using the computer program DRAIN-2D,[2] developed at the University of California, Berkeley, with modifications for plotting introduced at PCA.[3] Inelasticity is allowed in the program by concentrated flexural "point hinges" which form at the ends of elements when the yield moment is exceeded at these points. The hysteretic moment-rotation relationship for these hinges is an extended version of Takeda's model which accounts for the observed decrease in reloading stiffness in reinforced concrete members subjected to reversed inelastic loading. The members were assumed to possess unlimited deformation capacity since a major objective of the study was the determination of deformation requirements.

After several alternative models were tried and the results compared with those for the full 20-mass model, it was decided to use the 12-mass model shown in Fig. 2. The masses in the model used are concentrated at each floor level for the first four floors from the base and at every other floor above these. In modelling the hinging region, the results obtained using the 12-mass model shown in Fig. 2, with the segment of the wall between masses taken as a single element, were compared with results corresponding to a model in which these segments were subdivided into shorter elements. This comparison indicated that the 12-segment model was adequate.

The integration time step used in the dynamic analyses was varied from 0.005 sec. for the short (0.8 sec.) period structures and certain input accelerograms to 0.02 for the longer period structures. Among the response parameters considered were the maximum values of horizontal displacement, interstory displacement, bending moment, shear, required rotational ductility and cumulative ductility.

RESULTS OF ANALYSES

(a) Frequency Characteristics of Input Motion. It was considered desirable early in the study to attempt a classification of input motions in terms of their frequency characteristics in order to reduce to a minimum the number of input motions to be used in obtaining near-maximum values due to variations in the other parameters. For this purpose, accelerograms were categorized as either "peaking" or "broad band" depending upon whether their 5% damped velocity response spectra exhibited dominant frequency components over a well-defined period range or remained more or less flat over the period range of interest, i.e., 0.5 sec. to 3.0 sec. Broad band accelerograms were in turn subdivided into "flat" when the velocity spectrum was relatively flat, and "ascending" when the spectrum ordinates increased with increasing period over the period range of interest.

On the basis of this classification, a series of analyses was carried out for different values of the fundamental period, T_1, and yield level, M_y, using selected accelerograms exhibiting both peaking and broad band characteristics. In all cases, an input motion intensity (measured in terms of the 5% damped spectrum intensity) equal to 1.5 that of the N-S component of the 1940 El Centro record and a duration of 10 seconds were used. Figure 3 shows the velocity response spectra of five of the normalized accelerograms used.

A comparison of the envelopes of maximum horizontal displacements due to the different input motions for the case of a structure with T_1 = 1.4 sec. and a relatively low yield level of 500,000 in-kips is shown in Fig 4a. Here, significant yielding occurs at the base of the wall and the E-W component of the 1940 EL Centro record, a "broad-band ascending" type of accelerogram, produces the greater response compared to the 1971 Pacoima Dam S16E component, which is a "peaking" accelerogram relative to the initial fundamental period of the structure of 1.4 sec. (see Fig. 3). The same relative severity of response occurs in the interstory displacement and the rotational ductility requirements. However, primarily because of the effect of higher mode response, the shears were more severe for the artificial accelerogram S1 and the peaking 1971 Holiday Orion E-W record than for the El Centro E-W component.

On the other hand, for structures with a relatively high yield level where a lesser degree of yielding occurs, the peaking accelerogram produces the more severe response. This is shown in Fig. 4b, for a structure with a yield level, M_y = 1,500,000 in-kips and a fundamental period of 0.8 sec., for which the N-S component of the 1940 El Centro record is a peaking type. In this case, the N-S component produces the more severe response in all the response quantities considered, including shear.

(b) Initial Fundamental Period of Structure. The effect of the initial fundamental period was investigated using values of T_1 = 0.8, 1.4, 2.0 and 2.4 sec., covering the practical range for 20-story buildings. Yield level values ranging from 500,000 in-kips to 1,500,000 in-kips, and a yield stiffness ratio of 0.05 were assumed for each fundamental period value. Envelopes of maximum horizontal displacements and rotational ductility requirements for the case of structures with a yield level, M_y = 500,000 in-kips are shown in Fig. 5, corresponding to the E-W component of the 1940 El Centro record. As observed by earlier investigators, there is a consistent increase in maximum (and interstory) displacement with increasing period or decreasing stiffness of the structure. Furthermore, the ductility requirements, expressed in terms of ductility ratios, increase with decreasing fundamental period. Figure 5b, however, indicates that beyond a certain value of the fundamental period, the ductility requirements do not decrease significantly with an increase in period. The maximum shear corresponding to the same yield level did not vary significantly over the period range considered.

(c) Yield Level. Values of the yield level considered ranged from M_y = 500,000 in-kips to 1,500,00 in-kips. Envelopes of maximum displacement and horizontal shear are shown in Fig. 6 for a structure with T_1 = 1.4 sec.

The following observations apply to the variations of maximum response with the yield level. For the same fundamental period, the horizontal and interstory displacements decrease sharply as the yield level increases from 500,000 in-kips to a value associated with nominal yielding at the base. Above this value, the trend is reversed and an increase in yield level is accompained by an increase in horizontal displacements. The maximum shears increase sharply with the yield level for structures with period equal to 0.8 and 1.4 sec. For higher periods (2.0 and 2.4 sec), the effect of the yield level on the maximum shear is rather negligible. As might be expected, the rotational ductility requirements increase significantly with decreasing yield level.

A plot of the maximum (base) shear and rotational ductility demand as a function of the fundamental, T_1, for M_y = 500,000 in-k is shown in Figs. 7 and 8 for different input motions. Figure 9 shows the base shear as a function of both the fundamental period, T_1, and the yield level, M_y. Also shown in the figure is the surface for the base shear as defined in UBC-73 for Z = 3, K = 1.33, I = 1.0, S = 1.0 and a load factor of 2.0. Note that the code base shear can be unconservative for the longer period, high yield level structures.

SUMMARY AND CONCLUSIONS

1. The choice of the type of input motion for determining the maximum dynamic response of a particular structure depends, among others, on the expected intensity of the ground motion and the yield level of the structure. Where only nominal yielding is expected, a "peaking" accelerogram is more likely to produce the more critical response. On the other hand, where extensive yielding is expected, a "broad band" accelerogram may provide a closer estimate of the maximum response, for the same intensity of motion. Of course, the choice of the type of accelerogram to use will also have to be based on considerations of probable epicentral distance and geology.

2. A direct result of increasing the stiffness of a structure and decreasing its fundamental period is the reduction of the interstory displacements as well as the interstory tangential deviations (which, for isolated walls, is a better measure of the distortion which the structure suffers) along the height of the structure. This explains the generally better performance with respect to damage control of buildings stiffened by structural walls compared to rigid frame buildings.

3. The ductility requirement, expressed in terms of the ductility ratio, θ_{max}/θ_y, generally increases with decreasing fundmental period (or increasing stiffness) of a structure, the increase being more pronounced for the lower yield levels. However, because of the lower absolute value of the displacements for the stiffer structure, the cumulative ductility, i.e., the summation of the inelastic displacements, is less for this structure.

4. The maximum shear force at the base of the wall, which can appreciably affect the deformation capacity of a reinforced concrete wall, generally is not affected significantly by the fundamental period of the structure. This is particularly true for structures of low yield levels. Increasing the yield level results in sharp increases in the base shear for structures with low periods although this effect diminishes for higher periods.

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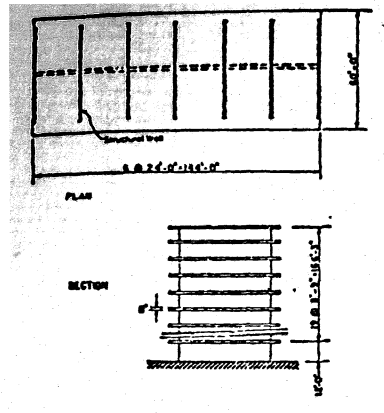

Fig. 1 - Twenty-story building with 'isolated' structural walls

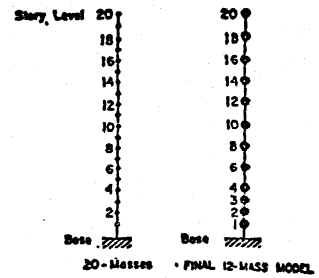

Fig. 2 - Dynamic analysis models

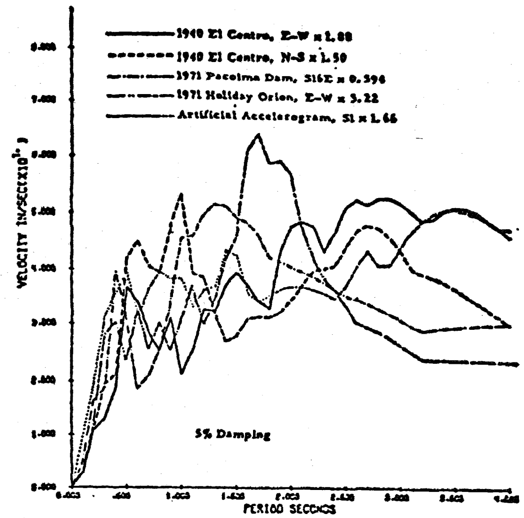

Fig. 3 - Relative velocity response spectra corresponding to first 10 seconds of normalized input motions

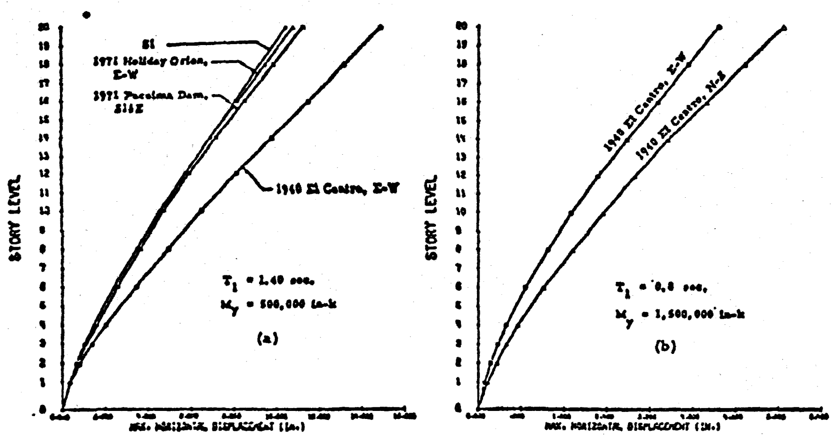

Fig. 4 - Response envelopes for wall with T_1 = 1.4 sec. and M_y = 500,000 in-k

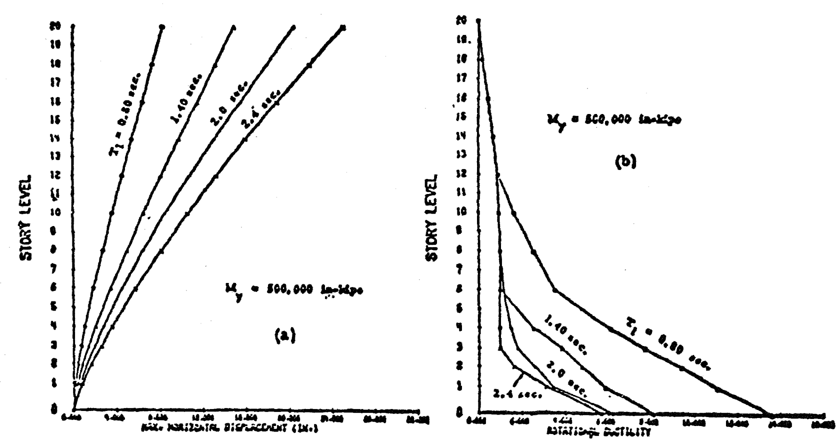

Fig. 5 - Response envelopes for wall with M_y = 500,000 in-k and varying period, T_1

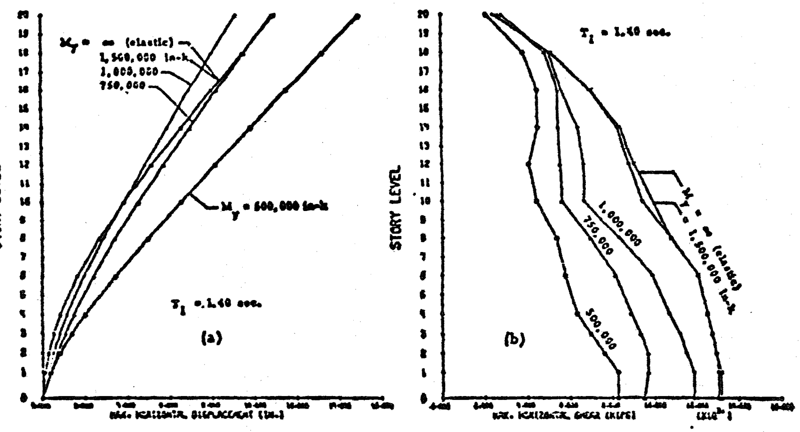

Fig. 6 - Response envelopes for wall with T_1 = 1.4 sec. and varying yield level, M_y

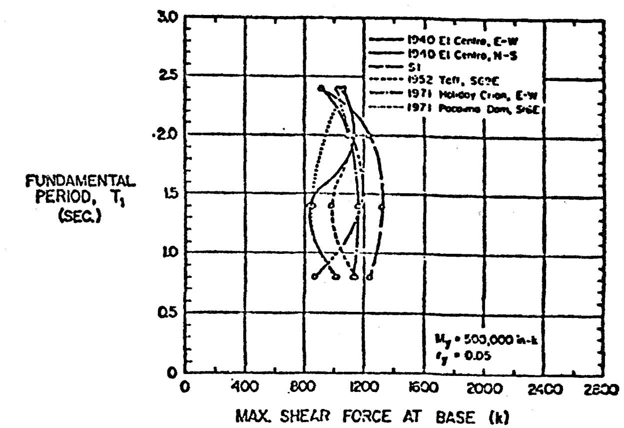

Fig. 7 - Maximum base shear as a function of T_1 for wall with M_y = 500,000 in-k

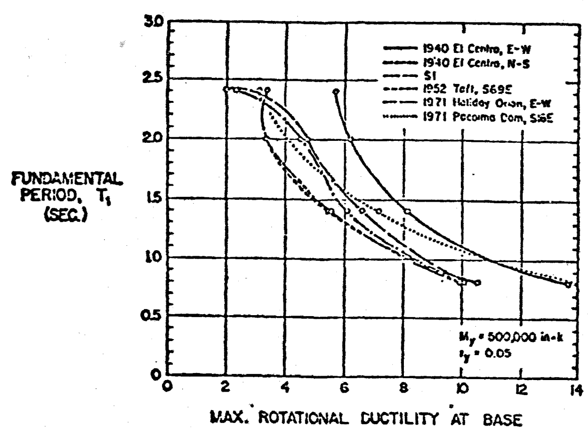

Fig. 8 - Ductility demand at base as a function of T_1 for wall with M_y = 500,000 in-k

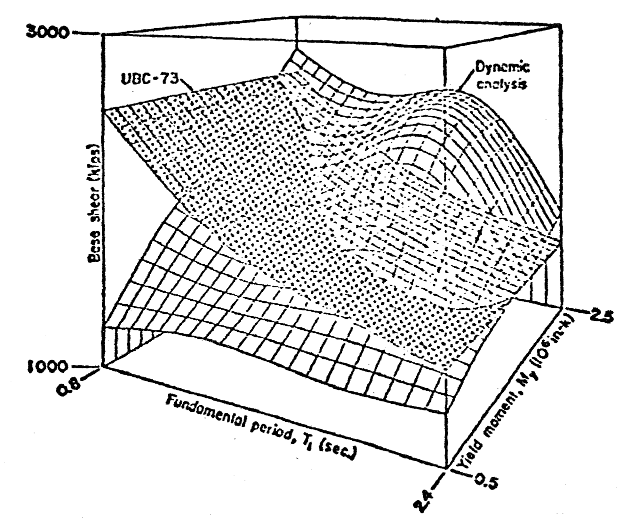

Fig. 9 - Maximum base shear as a function of both fundamental period, T_1, and yield level, M_y