DETERMINING DESIGN FORCE LEVELS FOR EARTHQUAKE-RESISTANT REINFORCED CONCRETE STRUCTURAL WALLS

by

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SUMMARY

A procedure for determining design forces for earthquake-resistant reinforced concrete structural walls is presented. Following an extensive parametric study to identify significant variables, a comprehensive series of dynamic inelastic analyses was made. Response data obtained from some 300 analyses served as basis for the procedure developed. The procedure applies specifically to isolated structural walls.

In determining design force levels, attention was focused on the critical hinging region near the base of the wall. Results of the analyses are correlated with data from tests on large-size wall specimens subjected to slowly reversing loads. The procedure developed differs from currently used or proposed methods in providing an explicit relationship between ductility, yield level, and corresponding design forces.

INTRODUCTION

Current code-specified forces for design of earthquake-resistant structures imply certain relationships between expected earthquake demand and structural capacity. Correlation of force and deformation demands and available capacities of different structures upon which these design forces are based, however, has not been fully established or adequately documented. The major difficulty is the lack of adequate information on earthquake demand. Also, more data are needed on structural capacity of particular structures. There is clearly a need to better define the variation of the significant "load" (earthquake demand) and "resistance" (structural capacity) quantities with the major variables for different types of structures and structural systems.

Investigation of reinforced concrete structural walls gained impetus from the observation that the dual requirements of life safety and damage control in multistory buildings can most efficiently be met by the use of structural walls. This observation has been repeatedly verified during recent earthquakes.

Work leading to the design procedure discussed in this paper was done to lay a firmer basis for the earthquake-demand-versus-structural capacity relationship. Results for the particular case of isolated structural walls are presented here. Subsequent phases of the project consider wall systems, i.e., coupled walls and frame-wall systems.

OBJECTIVE

The major objective of the investigation is to determine force and deformation demands in critical regions of isolated structural walls sub-

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jected to earthquake motions. A wide range of values of the significant structural and ground motion parameters is considered. Because the magnitude of inelastic deformation in critical regions of walls is a major design consideration, analysis must consider the inelastic phases of response.

GENERAL APPROACH

Parametric Study

As an initial step in developing the design procedure, an extensive parametric study was conducted to identify the most significant structural and ground motion parameters (1). Among the variables considered were: fundamental period, yield level in flexure, yield stiffness ratio, unloading and reloading stiffnesses characterizing the "decreasing-stiffness" hysteretic loop, damping, taper of stiffness and strength along height of structure, and base fixity condition. In addition to these structural parameters, effects of ground motion intensity, duration, and frequency content on dynamic inelastic response were also investigated.

Results of the parametric study indicate that among the structural variables considered, the most important are initial fundamental period and flexural yield level. Among the parameters characterizing ground motion, intensity is the most significant. However, frequency content can also have an appreciable effect on response. Ground motion duration primarily affects the cumulative plastic hinge rotation, by influencing the number of cycles of response.

Compilation of Response Data

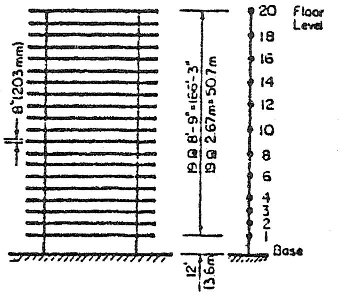
Once the principal variables had been identified through parametric studies, comprehensive dynamic response data were compiled. A wide range of values of the principal variables was considered. The purpose of this compilation was to establish the variation of selected response quantities with the major structural and ground motion parameters. A correlation with laboratory results could then follow.

Computer Program

Dynamic analyses were carried out using the computer program DRAIN-2D (2), developed at the University of California, Berkeley. The program is a general purpose code for dynamic analysis of plane inelastic structures. A number of modifications have been introduced into the program by Construction Technology Laboratories/PCA staff.

Analytical Model

An elevation of the basic 20-story isolated wall structure considered in the parametric study and in much of the subsequent series of analyses is shown in Fig. 1a. Preliminary studies indicated that it is permissible to use a lumped-mass model with 12 masses for the dynamic analysis (1). This reduced model is shown in Fig. 1b. Note that the nodes, as well as the lumped masses, in the lower critical region of the wall are spaced closer together than those above. This was done to obtain a more detailed estimate of deformation in this critical region. Similar reduced models were used for 10-, 30- and 40-story structures.



(a) SECTION A-A (b) 12-MASS MODEL

Fig. 1 Twenty-Story Isolated Structural Wall Model

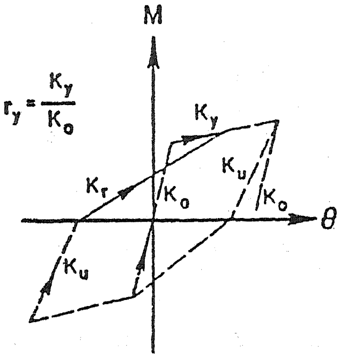


Fig. 2 Hysteretic Loop of Decreasing-Stiffness Model

The primary moment-rotation relationship assumed for the hinging region is bilinear. The hysteretic loop, shown in Fig. 2, is defined by rules essentially following those proposed by Takeda (3). The loop is characterized by decreasing slopes of the reloading and unloading branches in cycles subsequent to yield.

Input Motions

A total of five different recorded accelerograms and one artificially generated motion was used in the analyses. Input motions are characterized by three major parameters, namely, intensity, duration, and frequency content. The intensities of input motions were normalized in terms of "spectrum intensity" (SI). As used here, spectrum intensity is defined as the area under the 5%-damped relative velocity response spectrum corresponding to 10 seconds of ground motion, between periods 0.1 sec. and 3.0 sec. The spectrum intensity for the N-S component of the 1940 El Centro record was used as the reference spectrum intensity, $SI_{ref.}$. Intensity values equal to 0.75, 1.0, and 1.5 times $SI_{ref.}$ were considered.

After examination of available recorded motions and the literature on the subject of earthquake duration, a 20-second duration of strong ground motion was selected to provide a basis for design. In this study, an approximate method of classifying accelerograms with respect to frequency content based on the shape of the associated 5%-damped velocity spectrum is proposed. Results of the parametric study (1) indicate that the method provides a good basis for selecting input motions for near-maximum response.

DETERMINATION OF DESIGN FORCE LEVELS

Once the major variables affecting inelastic dynamic response had been identified through parametric studies (1), an extensive series of analyses was carried out. Over 300 such analyses were performed. The aim here was to compile response data corresponding to a wide range of values of the major variables. Response quantities of interest include maximum top displacement, interstory displacement, maximum shear, maximum bending moment, and rotational ductility in the critical hinging region near the base of the wall.

Maximum Response Values

To compile data on maximum response values, six different accelerograms were selected. Main structural variables considered are initial fundamental period, T_1, and flexural yield level, M_y. The fundamental period was assigned values ranging from 0.5 sec. to 3.0 sec. Yield level values from 150,000 in.-kips (16,950 kN·m) to 3,000,000 in.-kips (339,000 kN·m) were considered. In addition to the 20-story wall considered in the parametric studies 10-, 30- and 40-story structures were analyzed.

Results of the dynamic analyses have been assembled in the form of plots giving maximum response quantities as functions of the fundamental period T_1, and yield level, M_y. Selected plots of maximum top displacement, shear, and rotational ductility demand, for the case of 20-story structural walls with M_y = 750,000 in.-kips (84,750 kN·m), are shown in Fig. 3.

Critical Response Values

From plots of maximum response values due to different input motions, such as shown in Fig. 3, a second set of figures was prepared. This second set shows only the largest response values due to any of the different input motions used in Fig. 3. These will be referred to as "critical" response values. Examples of critical response plots for 20-story isolated walls are shown in Fig. 4. A curve for a specific yield level in Fig. 4 is defined by points representing the largest values of the parameters in the maximum response plots. Thus, a maximum response plot, such as Fig. 3a, showing maximum response due to several input motions and corresponding to a particular yield level, M_y, provides one curve in the corresponding critical response plot of Fig. 4.

Figure 4b indicates that rotational ductility demand decreases with increasing strength or yield level and increasing fundamental period. On the other hand, Fig. 4c indicates that as yield level increases, maximum shear also tends to increase. Thus, an increase in strength or yield level has two counteracting effects, one tending to diminish ductility demand and the other tending to increase maximum shear in the hinging region. Experiments (4, 5) have shown that high shears can limit the rotational capacity (or ductility) fo the hinging region in walls subjected to reversed loading.

DESIGN PROCEDURE

The procedure for determining design force levels for isolated structural walls is based on critical response plots such as shown in Fig. 4. Figures 5 and 6 show design charts developed for walls of 10 to 40 stories subjected to an earthquake intensity equal to 1.5 $SI_{ref.}$. The method used in obtaining Figs. 5 and 6 from critical response plots is relatively straightforward and is described in detail in Ref. 6.

Basic design steps using Figs. 5 and 6 are as follows:

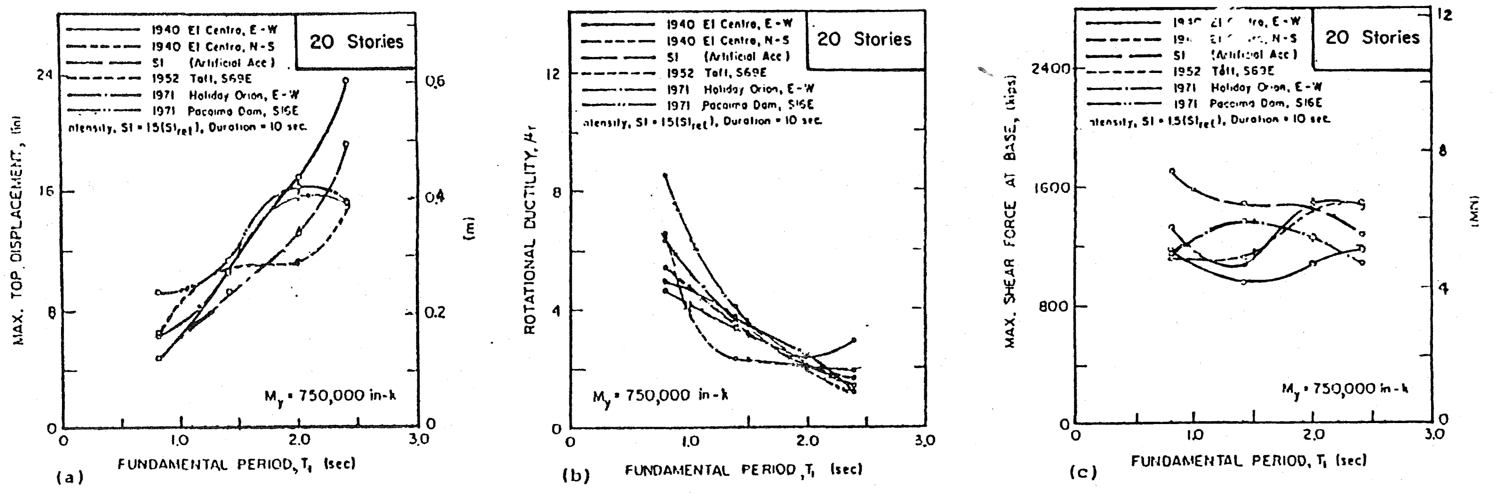


Fig. 3 Maximum Response Values for 20-Story Isolated Walls - SI = 1.5 ($SI_{ref.}$)

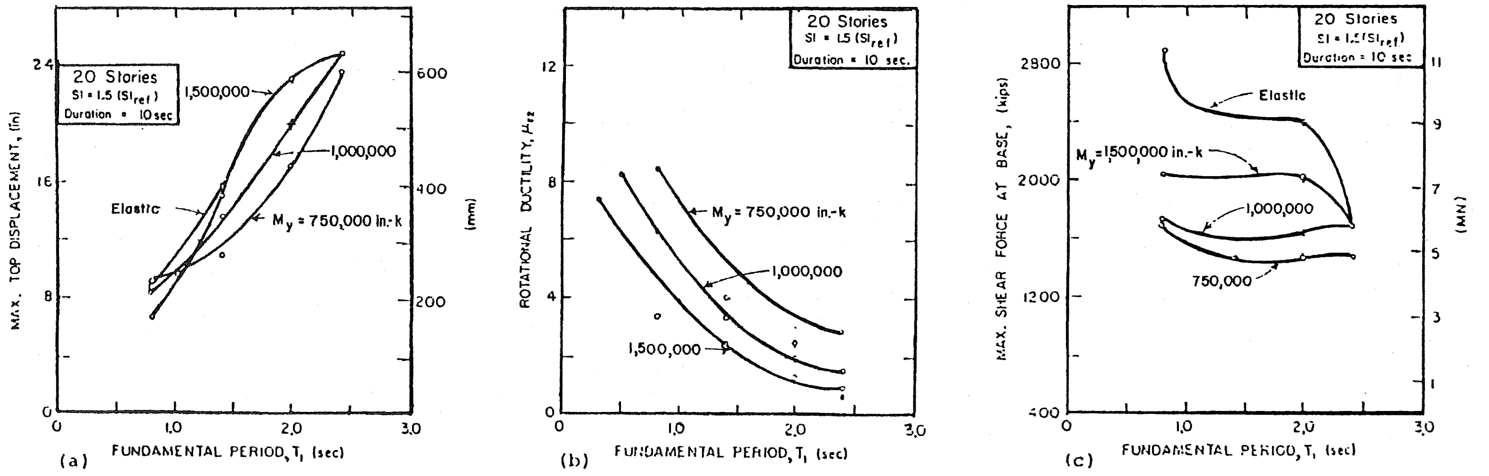


Fig. 4 Critical Response Values for 20-Story Isolated Walls - SI = 1.5 ($SI_{ref.}$)

1. Starting with a preliminary design satisfying gravity and wind loading requirements, assume an available rotational ductility, μ_r^a. An estimate may be obtained by using a chart based on experimental data (4, 5) similar to the plot shown in Fig. 8. The estimate is obtained by entering the chart with an assumed value of the design nominal shear stress.

2. Determine flexural design factor, α_f, from a chart such as is shown in Fig. 5. The total lateral force for flexural design, $V_T = \alpha_f W$ (W being the effective weight of the wall) is then distributed over the height of the wall according to UBC-76 (7), as shown in Fig. 7. Flexural reinforcement required to provide the minimum yield level, M_y^{min}, at the critical section near the base of the wall can then be calculated. Provision of M_y^{min} at the critical section is intended to ensure that the available rotational ductility assumed in Step 1 is not exceeded under the design earthquake intensity.

3. Determine the shear design factor, $\overline{\alpha}_v$, from a chart such as shown in Fig. 6. Using $\overline{\alpha}_v$, and a reduction factor, r_v*, calculate effective static shear $V_s = r_v\overline{\alpha}_v V_T = r_v\overline{\alpha}_v\alpha_f W$.

4. Check if the available ductility, μ_r^a, assumed in Step 1 can be developed under the design shear stress corresponding to the shear determined in Step 3 above. This check can be done using a chart, such as shown in Fig. 8, based on experimental data.

   If the assumed ductility can be developed, then determine the required shear reinforcement. This will be based on design recommendations from results of the experimental program (4, 5).

5. If the assumed ductility cannot be developed under the calculated design shear stress, adjust the assumed ductility value accordingly and repeat Steps 1 through 4 until reasonable agreement between assumed and available ductilities is obtained.

These design steps are for the critical region at the base of an isolated structural wall. Specifically considered are the forces necessary to determine flexural and shear reinforcement. Assumed as known or specified are the funadamental period of the structure and the design earthquake intensity.

A major distinction between the proposed procedure and current simplified design procedures is the explicit relationship established between the principal structural parameters and force and deformation requirements. Also important is the manner in which these have been correlated with experimental data to obtain design forces. A design procedure for frame-wall systems can be developed along similar lines, with appropriate modifications to reflect the effect of other structural parameters characterizing the more complex systems. This is the subject of a current program of investigation.

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*This reduction factor is applied to the calculated critical dynamic shears to account for the effect of a number of factors and allow a direct comparison with shear strength values obtained experimentally under slowly reversed loading.

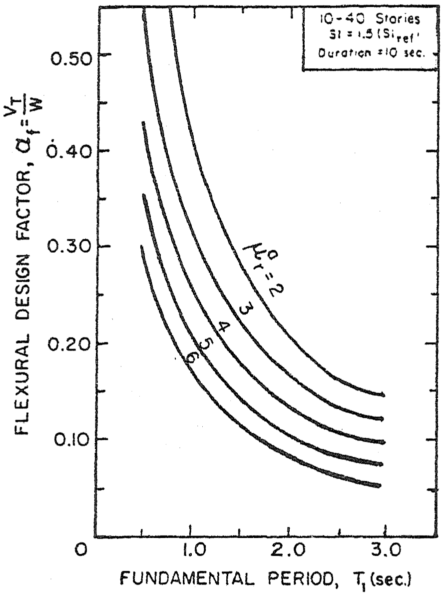

Fig. 5 Flexural Design Factor, α_f

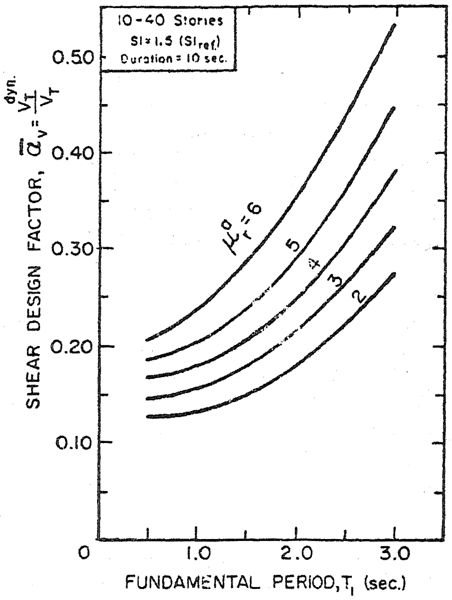

Fig. 6 Shear Design Factor, $\bar{\alpha}_v$

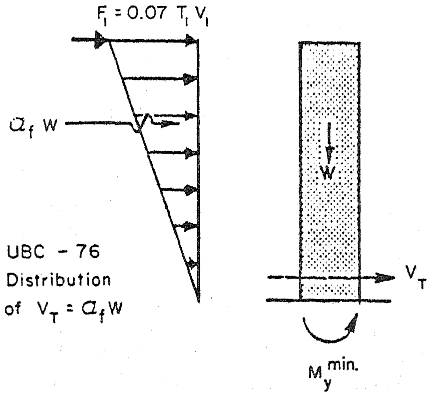

Fig. 7 Distribution of Lateral Forces Along Height of Isolated Structural Walls

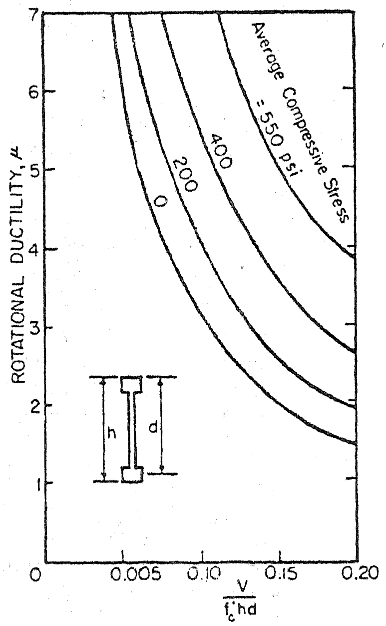

Fig. 8 Rotational Ductility Ratio, μ_r

SUMMARY

A procedure for determining design force levels for earthquake-resistant isolated structural walls is described. The method is based on a correlation of analytically-derived earthquake demands and capacity values obtained from the concurrent experimental program. The procedure developed differs from current code procedures in providing an explicit relationship between the principal structural and ground motion parameters and the corresponding force and deformation demands.

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