DESIGN REQUIREMENTS FOR STRUCTURAL WALLS IN MULTISTORY BUILDINGS

A. T. Derecho (I)
W. G. Corley (II)
Presenting Author: A. T. Derecho

SUMMARY

A procedure for proportioning earthquake-resistant reinforced concrete structural walls in multistory buildings is presented. Results from an extensive series of analyses for force and deformation demands corresponding to a wide range of structural and ground motion parameters as well as capacity values obtained from tests of large-size specimens subjected to reversed cycles of loading form the bases of the design procedure. In both analyses and tests, emphasis was placed on the critical region near the base of the structural wall. The investigation reported here is part of a combined analytical and experimental program sponsored by the National Science Foundation.

INTRODUCTION

Reinforced concrete structural walls represent an economical method of strengthening and stiffening multistory buildings against lateral forces. When properly designed, structural walls or shear walls can serve as the principal lateral-load-resisting element in a building, providing not only the strength to resist lateral forces but also the stiffness to reduce interstory drift and minimize damage to nonstructural components during an earthquake.

This investigation is one of several sponsored by the National Science Foundation to generate information on structural walls for earthquake-resistant multi-story buildings. The work reported here was undertaken to provide information on earthquake demands at the critical region of isolated structural walls as well as strength and deformation capacity of walls subjected to reversed cycles of loading.

GENERAL APPROACH TO DEVELOPMENT OF DESIGN PROCEDURE

The twin design requirements relating to demand (loading) on the one hand and capacity (resistance) on the other were investigated in a combined analytical and experimental program. Development of information on demands at critical hinging regions of walls was the primary aim of the analytical phase of the investigation. Capacity values relating to strength and ductility were to be obtained by laboratory tests.

(I) Consultant, Wiss, Janney, Elstner Associates, Inc., Northbrook, Illinois; formerly, Manager, Structural Analytical Section, Engineering Development Division, Portland Cement Association, Skokie, Illinois.

(II) Divisional Director, Enginering Development Division, Construction Technology Laboratories, Portland Cement Association, Skokie, Illinois.

Major requirements that were set to guide the development of the design procedure, particularly with respect to demand values, were:

1. The force and deformation requirements that were to serve as bases for the procedure should represent "near-maximum" values corresponding to the most severe response to a selected number of input accelerograms.

   It was recognized that it was not possible, nor did it seem necessary, to define the absolute maximum response values for a given set of practical conditions. However, it was considered important to ensure that the response values obtained were reasonably close to the maximum.

2. The information on demands should reflect the influence of significant parameters affecting response.

3. The design procedure to be developed should be simple enough to be useful in a practical design environment. Consequently, it was considered important to include in the formulation only the most significant parameters.

To obtain data on force and deformation demands for use in design, an initial study was carried out to enable characterization of input motions in terms of their relative velocity response spectra (Ref. 1). The immediate aim of this initial study was to provide a basis for selecting a few representative accelerograms that could be used as input in calculating critical or "near-maximum" response values. Two basic types of accelerograms were identified for this purpose based on the relationship between spectrum shape and the dynamic response of single-degree-of-freedom (SDF) inelastic systems.

Following the initial study, a parametric investigation was carried out to identify the most significant structural and ground motion parameters on which the design procedure could be based. Structural parameters considered included fundamental period, flexural yield level, yield stiffness ratio, character of M-ϕ curve, damping, strength taper, stiffness taper, base fixity condition and number of stories. Six input motions having different frequency content characteristics were used in the parametric study and in the subsequent analyses to compile response data for design. These accelerograms had a cosntant duration of ten seconds and were normalized with respect to intensity using Housner's "spectrum intensity" (Ref. 2). The spectrum intensity (SI) corresponding to the N-S component of the 1940 El Centro (Imperial Valley earthquake) record was used as the reference measure, $SI_{ref.}$ ($SI_{ref.}$ = 70.15 inches or 1,782 mm.)

Once the major parameters had been identified, an extensive series of dynamic inelastic analyses was carried out to compile response data for a wide range of values of fundamental period, flexural yield level and earthquake intensity. The design procedure developed is based on a correlation of these analytically-derived estimates of demand and experimentally-obtained capacity values. Experimental data, expressed in terms of rotational capacity under specific levels of shear stress, were obtained from tests of large-size specimens subjected to slowly reversed loading.

Charts for design base moments and shears are presented as functions of the initial fundamental period and available rotational ductility for a specific earthquake intensity. A method of adjusting design values corresponding to the reference intensity for other earthquake intensities is presented.

Results are applicable not only to isolated structural walls but also to wall-frame systems where the wall constitutes the dominant lateral-load-resisting element or to coupled wall systems with weak coupling so that axial load effects may be neglected. Many cases encountered in practice fall under these categories.

COMPILATION OF CRITICAL RESPONSE VALUES

The primary purpose of the analytical investigation was to obtain sufficient information on force and deformation demands in the critical hinging region of structural walls which, in conjunction with laboratory data on capacity, could serve as bases for a design procedure. Only the principal results of the investigation are presented here. Details can be found in Refs. 1, 3 and 4.

Analytical Model

The model considered in the dynamic analyses represents a single wall of a structure consisting of a series of identical parallel walls. Figure 1 shows the 12-mass model for a typical 20-story structure considered. The hysteretic moment-rotation relationship for the wall, incorporating Takeda's rules for decreasing stiffness for loading cycles subsequent to yield, is depicted in Fig. 2. The input motion is assumed applied to the base of the fixed-base system.

Dynamic time-history analyses were carried out using the computer program DRAIN-2D developed at the University of California, Berkeley, with post-processing modifications introduced by the Portland Cement Association.

In compiling response values, attention was focused on the hinging region near the base of the wall. After considering the relative merits of using alternative measures of inelastic flexural deformation, including rotational ductility, cyclic rotational ductility, cumulative rotational ductility, and cumulative rotational energy, it was concluded that the simple conventional measure, namely rotational ductility, $\mu = \theta_{max}/\theta_y$, was reasonably representative of the other measures. This measure of inelastic deformation was adopted throughout the investigation. Observations of tests on walls indicated that most of the inelastic deformation is concentrated within a height approximately equal to the horizontal length of the wall.

Consequently, a hinging height equal to the horizontal length of the wall was assumed in the analyses. The hinging height varied with the overall height of the wall since greater horizontal lengths were assumed for the taller walls.

Design Charts

Results of extensive analyses aimed at generating response data for design are shown in Figs. 3 and 4. These figures present values of coefficients for the flexural and shear design of the critical region near the base of an isolated wall. The coefficients are given as functions of the initial fundamental period, T_1, and available ductility, μ_r^a, at the base of the wall.

The flexural design factor, $_f$, represents the ratio of the total lateral force, V_T, to the weight of the wall, W. Distribution of the lateral force, V_T, along the height of the wall is to be in accordance with provisions of the Uniform Building Code (1982 Edition) governing distribution of the base shear over the height of a building. The base moment, M_y^{min}, produced by the distributed lateral force represents the minimum flexural capacity that must be provided at the base if the assumed available ductility is not to be exceeded under the design earthquake intensity. Figure 3 shows that the design lateral force V_T decreases with increasing period and available ductility.

For the shear design of the base of the wall, Fig. 4 shows that shear coefficient, α_v, as a function of the fundamental period and available ductility. The factor α_v represents the ratio of the calculated maximum dynamic shear to the lateral force V_T used in design for flexure. What is important to note is that α_v is generally greater than unity, and can be as high as 3.5 for the longer period structures.

Since Figs. 3 and 4 were obtained by a smoothing process, it became important to determine how the final results given in these figures compared with the original data. Figures 5 and 6 show comparisons of values from Figs. 3 and 4 with the original data for 175 cases. Both Figs. 5 and 6 indicate that the proposed design values are less than the corresponding calculated maximum values in 3% of the cases, the underestimate being as much as 15%. It is believed that this difference is acceptable and within the range of uncertainty associated with effects of other variables not specifically included in the figures or with the estimates of available ductility and earthquake intensity.

Correlation with Experimental Data - Design of Base of Wall

To apply the information contained in Figs. 3 and 4 to the design of a structural wall, an estimate of the available ductility at the base of the wall is needed. Figure 7, based on tests of large-size walls subjected to slowly reversed loading (Ref. 5) provides a basis for estimating the available rotational ductility at the base of a wall as a function of the nominal shear stress.

The design process consists of estimating the maximum nominal shear stress at the base of the wall and using Fig. 7 to obtain a value of available ductility. Corresponding to this estimated available ductility, Fig. 3 gives the forces (distributed according to UBC-82) necessary to determine the design base moment. Figure 4 gives the design base shear. The nominal shear stress corresponding to the design base shear is then compared to that initially assumed. Necessary adjustments are made if the calculated shear stress differs significantly from the assumed value. The cycle of calculations is repeated until reasonable agreement is reached between assumed and derived values of shear stress.

A detailed description of the application of Figs. 3, 4 and 7 in design is given in Ref. 4. It is pointed out that there is some justification for reducing the value of the shear design factor α_v for use in design (Ref. 4).

Design Forces for Upper Portions of Walls

Reference 4 describes a procedure for adjusting the design forces derived from Figs. 3 and 4 to obtain moments and shears along the height of the wall consistent with results of analyses.

Adjustments for Varying Earthquake Intensity

Results plotted in Figs. 3 and 4 correspond to an earthquake intensity equal to 1.5 times the reference intensity, SI_{ref}. In this study, SI_{ref} is taken as the spectrum intensity corresponding to the first 10 seconds of the N-S component of the 1940 El Centro (Imperial Valley earthquake) record. Following Housner, spectrum intensity is defined as the area under the 5% damped relative velocity response spectrum of an accelerogram, between periods 0.1 sec. and 3.0 sec.

To extend the use of Figs. 3 and 4 to design earthquakes of varying intensity, a number of 20-story walls were analyzed using different earthquake intensities. The walls considered represented different combinations of fundamental period and yield level. Results of the analyses are shown in Figs. 8 and 9. A linear relationship between the intensity correction factors for both flexural and shear design coefficients is proposed, as indicated in the figures.

Adjustments for Partial Base Fixity

The response of structural walls to lateral loading may be significantly affected by the degree of rotational restraint that may be developed at the base. This deviation from the common assumption of a fully-fixed base generally results from compliance of the foundation material under compressive loading due to lateral loads. It is pointed out that Figs. 3 and 4 correspond to walls fully fixed at the base. To examine the influence of degree of base fixity on the design forces, analyses were made, again using 20-story walls, assuming base fixity factors of 0.50 and 0.75. The base fixity factor, F_B as used in this study is defined as the ratio of the moment developed at the base of a particular wall due to a specified lateral displacement to the moment that would be developed if the base were fully fixed. The fully fixed condition corresponds to $F_B = 1.0$.

Results of the analyses assuming varying degrees of base fixity are shown in Fig. 10. This figure gives the correction factor to be applied to the flexural design coefficients for the fully-fixed-base structure, as given in Fig. 3. As might be expected, Fig. 10 shows that the flexural design force decreases with decreasing base fixity. A similar figure corresponding to the shear design coefficient is also available (Ref. 4).

CONCLUDING REMARKS

Results of an investigation designed to provide information on force and deformation demands in isolated structural walls subjected to earthquake loading are presented. The use of these results for the design of earthquake-resistant walls in conjunction with experimental data on available rotational ductility is described briefly.

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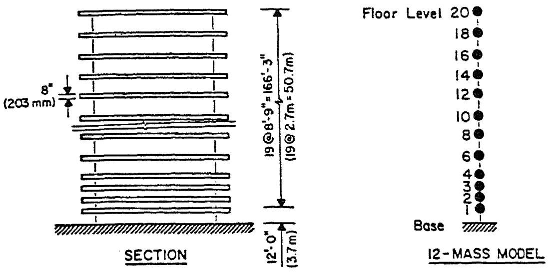

Fig. 1 Analytical model of 20-story structural wall

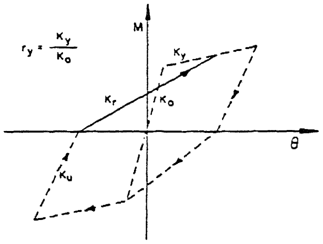

Fig. 2 Moment-rotation relationship showing decreasing stiffness characteristic

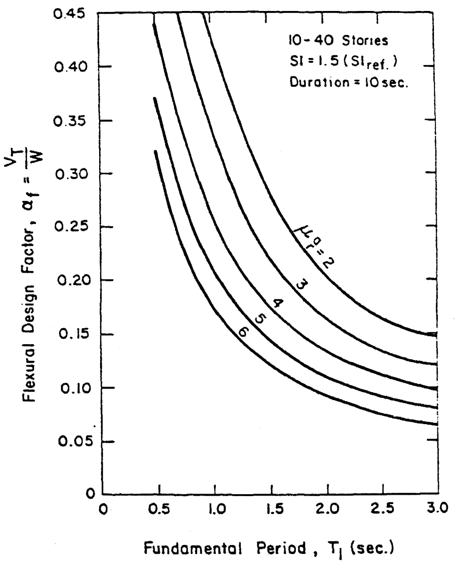

Fig. 3 Flexural design factor - 10-40 story walls

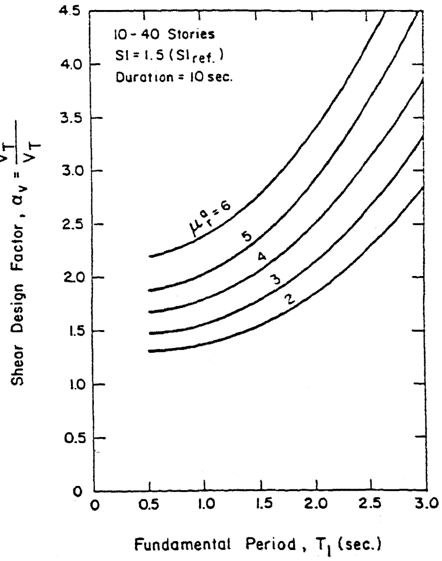

Fig. 4 Shear design factor - 10-40 story walls

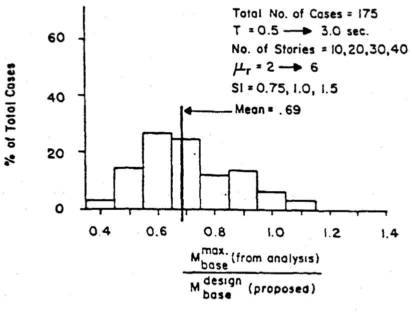

Fig. 5 Comparison of proposed design base moments with corresponding calculated maximum base moments

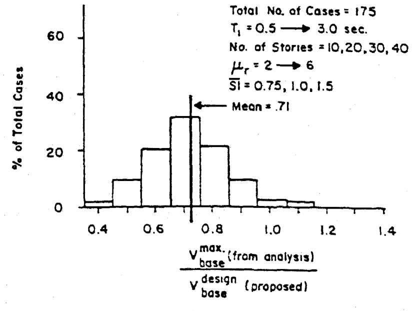

Fig. 6 Comparison of proposed design base shears with corresponding calculated maximum base shears

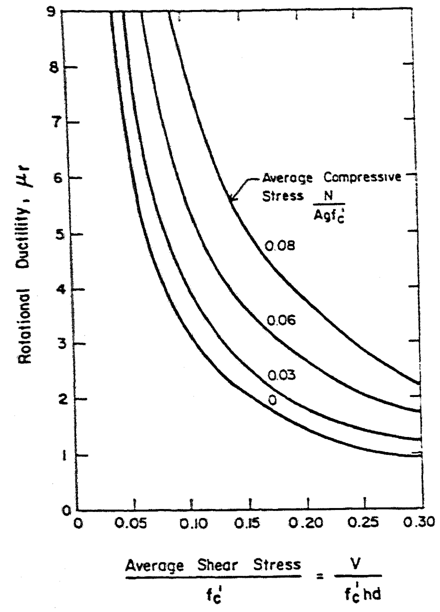

Fig. 7 Available rotational ductility as a function of maximum shear stress - based on test results

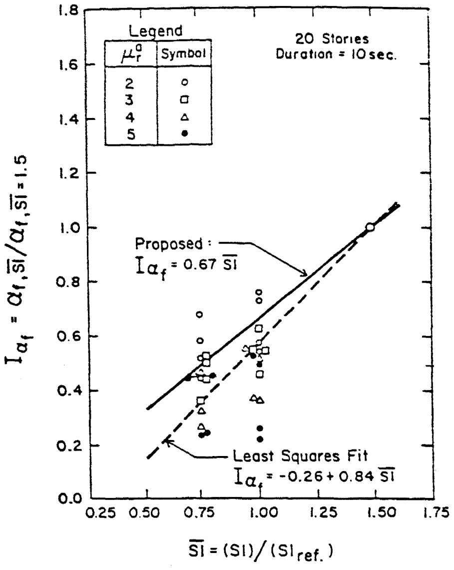

Fig. 8 Intensity factor for flexural design coefficient - 20-story walls

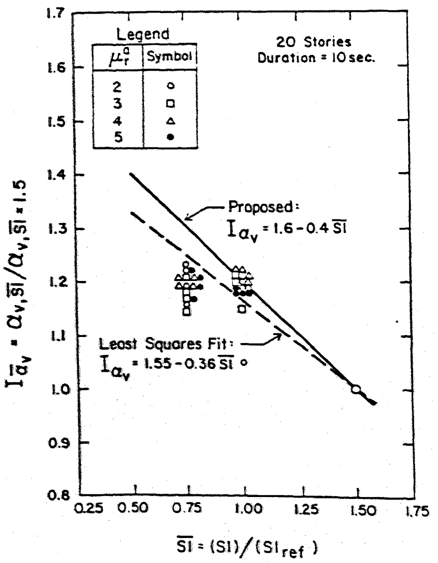

Fig. 9 Intensity factor for shear design coefficient - 20-story walls

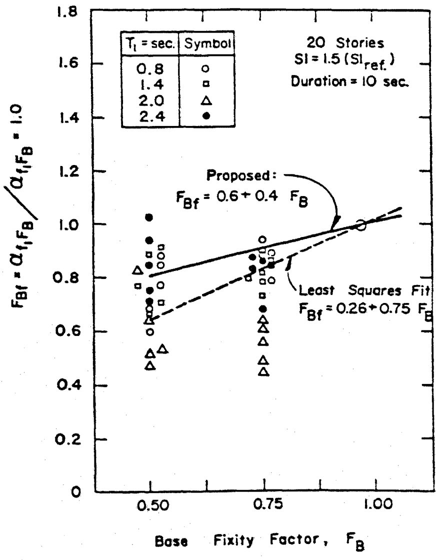

Fig. 10 Base fixity factor for flexural design coefficient - 20-story walls