SEISMIC DESIGN FOR REINFORCED CONCRETE WALLS

R. G. Oesterle (I)
A. E. Fiorato (II)
<u>Presenting Author</u>: R. G. Oesterle

SUMMARY

This paper presents a description of effects of design parameters on response of structural walls to earthquake loading. Experimental data are related to design criteria for flexural and shear strength and to the need for a reasonable balance between strength and deformation capacity.

INTRODUCTION

Performance of structural walls subjected to earthquakes is a function of stiffness, strength, deformation capacity, and deformation demand. Selection of strength for a given earthquake has a significant effect on wall response. Increasing strength reduces deformation demand. Therefore, structural walls must be designed as ductile elements with an efficient balance between yield strength and inelastic deformation capacity. To attain this balance, knowledge of behavior of walls under seismic load is essential.

This paper describes a test program undertaken to determine the effects of design parameters on strength and deformation capacity of structural walls. Observed results demonstrate the performance of structures subjected to earthquake loading.

TEST PROGRAM

The test program (Ref. 1) was a partial parametric investigation with the specimen representing a basic element of a structural wall system. Dimensions of the test specimens are shown in Fig. 1. Each specimen was loaded as a vertical cantilever with a reversing concentrated horizontal load at the top. Flanged, barbell, and rectangular cross sections were investigated. Nominal cross sectional dimensions are shown in Fig. 2. Figure 3 shows the type of reinforcement used in the specimens. Although floor slabs were not simulated, proportions of the test specimen were selected to represent a five-story wall.

A total of 21 wall specimens were tested to destruction. Experimental variables include, load history, section shape vertical and horizontal reinforcement, confinement reinforcement, moment-to-shear ratio, axial compressive stress and concrete strength.

(I) Manager, Analytical Design Section
(II) Director, Concrete Materials Research Department, Construction Technology Laboratories or the Portland Cement Association, Skokie, Illinois

OBSERVED EFFECTS OF TEST VARIABLES

The following is a discussion of the observed effects of variables on behavior and capacity of walls:

Load History

For walls subjected to inelastic load reversals, flexural capacities can be up to 15% less than monotonic flexural capacities. Figure 4 shows data on measured and calculated flexural capacities. Calculated capacities represent monotonic flexural strength. As can be seen in Fig. 4 walls subjected to monotonic load (denoted by the letter M) have measured capacities that are close to calculated capacities.

A larger deformation capacity is obtained for walls under monotonic loading as compared to that obtained under large numbers of inelastic load reversals. However, as noted by Bertero, high levels of deformation capacity may not be "usable" because of stability limitations (Ref. 2). For walls subjected to inelastic reversals, the sequence of application of large and small cycles had little effect on results. Behavior of the walls is more dependent on the level of prior maximum deformation sustained by the wall than on the sequence of load application.

Section Shape

Wall tests have included three basic section shapes identified as rectangular, barbell, and flanged (Ref. 1). These shapes are shown in Fig. 2. The rectangular shape generally provides less flexural capacity for equivalent wall proportions when compared to other shapes. There is a limit to the amount of reinforcement that can be physically placed in the end regions of a rectangular wall. Therefore, maximum flexural capacity is low relative to the maximum attainable in a barbell or flanged section of equal horizontal length and web width. Also, for equivalent moment-to-shear ratios, the level of shear stress in webs of rectangular walls will generally be lower than that for barbell or flanged sections. Slenderness of rectangular walls must also be considered, because this shape is more susceptible to lateral instability of the compressive zone under severe load reversals (Ref. 1, 2).

The barbell shaped section represents a wall between two column lines. Column boundary elements provide relatively large in and out-ofplane stiffness. These elements limit sliding shear by acting as large dowels. Since the enlarged boundary elements provide space for reinforcement in the end regions of walls, relatively high flexural capacities can be developed with this shape. Therefore, relatively high nominal shear stresses can be developed in barbell shaped walls. Web crushing generally limits shear capacity of this type section.

The flanged shape represents a section resulting from intersecting walls. As with the barbell section, the flanged shape can lead to a design with high shear stresses and web crushing as a limiting mode on shear capacity. Residual capacity of flanged walls, after web crushing, is a function of design and detailing of the boundary element at ends of the wall. For flanged sections, there is a tendency for the boundary element in compression to "shear through" after web crushing.

Flexural Reinforcement

The amount of vertical flexural reinforcement controls moment capacity of the wall section and, thus, the maximum level of applied shear. In design for earthquake resistance, it is necessary to recognize that shear forces developed in a wall are related to actual flexural capacity not design flexural capacity. Figure 5 shows the relationship between design strength and actual measured strength. Present designs may under estimate flexural capacity because actual yield stress of reinforcement is normally greater than the specified minimum. Also, strain hardening of reinforcement and distributed vertical web reinforcement are factors normally neglected in calculating design flexural strengths. Thus, if inelastic response occurs, the overturning moment on foundations and the level of shear forces induced may be significantly higher than anticipated.

For the same total amount of vertical reinforcement, walls having bars concentrated near their ends develop higher moment capacity and ultimate curvature than walls with uniformly distributed reinforcement (Ref. 3). Concentrations of vertical reinforcement near end regions of the wall can be used to form vertical boundary elements. Boundary elements resist sliding shear by providing stiff dowel elements at each end of the wall. They also provide residual capacity in case of web crushing.

Shear Reinforcement

Present code provisions for shear are based primarily on tests of walls under monotonic load (Ref. 3). Concrete and reinforcement contributions to resistance are developed to prevent diagonal tension failures. Wall tests under cyclic loads indicate that present code provisions are adequate to prevent occurrence of diagonal tension failures under earthquake type loadings.

Figure 6 gives a comparison between measured wall shear capacities and design values (Ref. 1, 3, 4, 5, 6). Using a capacity reductions factor $\phi = 0.85$ all measured strengths exceed design strengths. A capacity reduction factor of 0.6 has been proposed for cases where shear is anticipated to govern behavior. As can be seen in Fig. 6, this would provide an extremely conservative estimate of shear capacity.

Others have suggested that the "concrete contribution" to shear resistance be eliminated in seismic design of walls (Ref. 7). Elimination of the "contribution" would result in adding horizontal reinforcement. Results of wall tests do not support the need for additional horizontal reinforcement to prevent diagonal tension failures.

Sliding shear and web crushing are other potential shear failure modes. Horizontal bars are ineffective in resisting sliding shear. Also, tests indicate that additional horizontal steel does not have a significant effect on web crushing strength (Ref. 1).

Special Transverse Reinforcement

Present building codes require earthquake-resistant structural walls to be detailed with special transverse reinforcement in boundary elements over the entire wall height. Such transverse confinement reinforcement is illustrated in Fig. 3. Design criteria are based on providing confinement to increase concrete strain capacity.

The function of transverse reinforcement as confinement can be important for walls with relatively low concrete strength, high percentages of vertical reinforcement, and significant axial compression. Analysis indicates that special transverse reinforcement is needed as confinement when the neutral axis depth, determined from sectional analysis, exceeds 15% of the horizontal length of the wall.

Structural wall tests (Ref. 8) demonstrate that, in addition to providing confinement to increase concrete strain capacity, transverse reinforcement serves the following primary functions (Ref. 1):

(a) It supports vertical reinforcement against inelastic buckling

(b) Along with vertical bars, it contains fractured concrete within the core

(c) It improves shear capacity and stiffness of boundary elements

However, beneficial effects of special transverse reinforcement on these functions were not observed in tests until interstory drifts greater than 2% were attained. Since interstory drift limits of 1 to 2% are considered reasonable maximums, special transverse reinforcement may not be required for functions other than confinement. However, there is uncertainty associated with prediction of both earthquake loading and deformations of reinforced concrete structures. For this reason, it is recommended that designers provide special transverse reinforcement in critical regions of walls built in regions of high seismicity. Special transverse reinforcement is only needed in critical regions where concentrated inelastic rotations are expected.

Moment-To-Shear Ratio

Figure 7 shows measured nominal shear strengths of walls as a function of moment-to-shear ratio. Generally, shear strength increases with lower moment-to-shear ratios. This is primarily attributed to the fact that for lower moment-to-shear ratios, flexural yielding may not occur prior to web crushing. Several recent tests by Paulay (Ref. 6) are shown in Fig. 7 as being governed by "sliding shear." For these specimens, flexural yielding occurred and load reversals eventually resulted in loss of shear transfer capacity.

Wall tests have shown that web crushing capacity of walls is a function of applied shear distortions as well as concrete strength. Also, observed shear distortions increase significantly when flexural yielding is exceeded. Therefore, higher shear stresses are attainable in low-rise walls if they do not yield in flexure.

Tests have also shown that as walls become shorter, vertical reinforcement becomes more effective than horizontal reinforcement for shear resistance. This result has been observed in walls with height-to-horizontal length ratios of 1.0, and becomes more significant in shorter walls.

Axial Compressive Stress

For walls loaded monotonically, axial compressive stress has been found to increase moment capacity and reduce ultimate curvature (Ref. 3). Somewhat different results have been found for wall specimens subjected to reversing loads. Under reversing loads, axial force increases moment and shear capacity (Ref. 1, 2). However, web crushing has been found to be dependent on both stress and deformation levels. Since axial load decreases shear distortions at equivalent rotations, walls with axial load sustain larger rotations prior to web crushing.

Concrete Strength

Concrete strength can have several effects on performance of walls. Concrete strength affects the extreme compressive fiber capacity, web crushing capacity, and abrasion resistance along crack interfaces. The first effect is accounted for in conventional flexural and axial load design.

Web crushing strength is commonly considered to be a function of concrete strength alone. However, results of wall tests (Ref. 1) have shown that web crushing is dependent upon both strength and deformation levels. It should be noted that observed web crushing failures were "ductile" shear failures in that they occurred after significant yielding of flexural reinforcement. The current ACI Code limit of 10 $\sqrt{f'_c}$ (psi) nominal shear stress may be unconservative to prevent web crushing in walls with low strength concrete and low axial load, if they are subjected to large inelastic deformations. The following relationship has been developed to calculate web crushing capacity in walls for lateral drifts of up to 2% (Ref. 9):

$$v_u = 0.14\ f'_c + \frac{N_u}{2\ l_w h}$$

$$\text{but}\quad v_u \leq 0.18\ f'_c$$

where f'_c = specified compressive strength of concrete, psi

h = overall thickness of wall web, in.

l_w = horizontal length of wall section, in.

N_u = axial load normal to cross section, lb

v_u = maximum nominal shear stress, psi

CONCLUSIONS

This paper presents an evaluation of design criteria and detailing for earthquake-resistant walls based on laboratory tests using simulated load histories. Test data provide information on effects of design parameters on observed damage levels and the "final" mechanism of resistance for walls. Test specimens generally sustain load cycles to large inelastic deformations prior to loss of load resistance. However, large deformation capacity may not be needed because of stability limitations.

In evaluating load vs deformation relationships of walls tested in terms of the 1 to 2% relative story drift limits considered reasonable by many engineers, it is apparent that walls tested can meet the drift criteria with reserve deformation capacity. It is then a matter of selecting details to provide a comfortable balance between strength and deformation capacity while maintaining a suitable margin of safety against some catastrophic event.

REFERENCES

1. Corley, W. G., Fiorato, A. E., and Oesterle, R. G., "Structural Walls," Publication SP-72, American Concrete Institute, Detroit, 1981, pp. 77-131.

2. Bertero, V. V., "Seismic Behavior of R.C. Wall Structural Systems," State-of-the-Art in Earthquake Engineering, 1981, Turkish National Committee on Earthquake Engineering, Ankara, Oct. 1981, pp. 375-382.

3. Cardenas, A. E., Hanson, J. M., Corley, W. G., and Hognestad, E., "Design Provisions for Shear Walls," Journal of the American Concrete Institute, Proc. Vol. 70, No. 3, March 1973, pp. 221-230.

4. Barda, F., Hanson, J. M., and Corley, W. G., Shear Strength of Low Rise Walls With Boundary Elements," Portland Cement Association Publication RD 043D, 1976.

5 Iliya, R., and Bertero, V. V., "Effects of Amount and Arrangement of Wall-Panel Reinforcement on Hysteretic Behavior of Reinforced Concrete Walls, University of California, Berkeley, Report UCB/EERC-80/04, 1980.

6. Paulay, T., Priestly, M. J. N., and Synge, A. J., "Ductility in Earthquake Resisting Squat Shear Walls," Journal of the American Concrete Institute, Proceedings Vol. 79, No. 4, July-Aug. 1982, pp. 257-269.

7. Paulay, T., "Earthquake-Resisting Shear Walls - New Zealand Design Trends," Journal of the American Concrete Institute, Proc. Vol. 77, No. 3, May-June 1980, pp. 144-152.

8. Oesterle, R. G., Fiorato, A. E., and Corley, W. G., "Effects of Reinforcement Details on Seismic Performance of Walls," Earthquakes and Earthquake Engineering: The Eastern United States, Ann Arbor Science, Ann Arbor, 1981, pp. 685-707.

9. Oesterle, R. G., Aristizabal-Ochoa, J. D., Shiu, K. N., and Corley, W. G., "Web Crushing of Reinforced Concrete Structural Walls," (Submitted to American Concrete Institute for Publication) 1982.

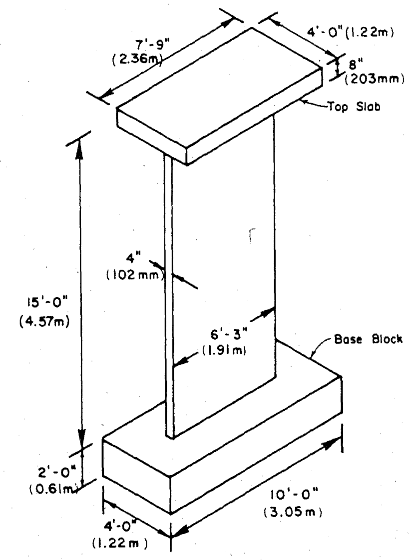

Fig. 1 Test Specimen

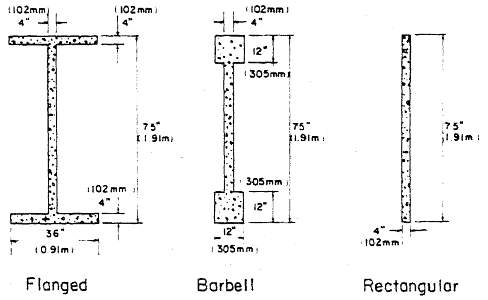

Fig. 2 Cross-Sections

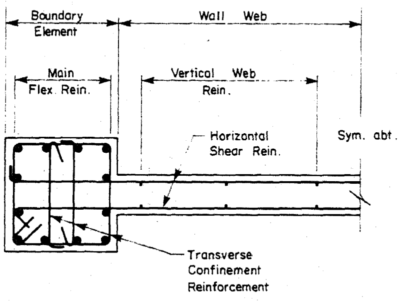

Fig. 3 Wall Section

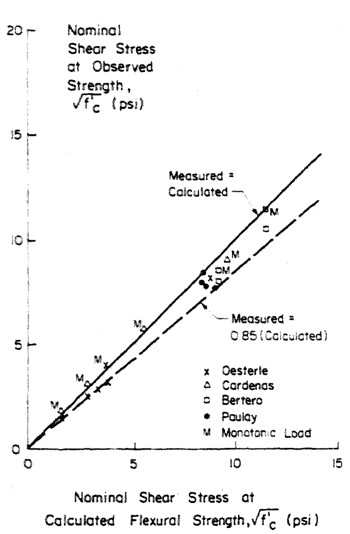

Fig. 4 Measured vs. Calculated Flexural Capacity

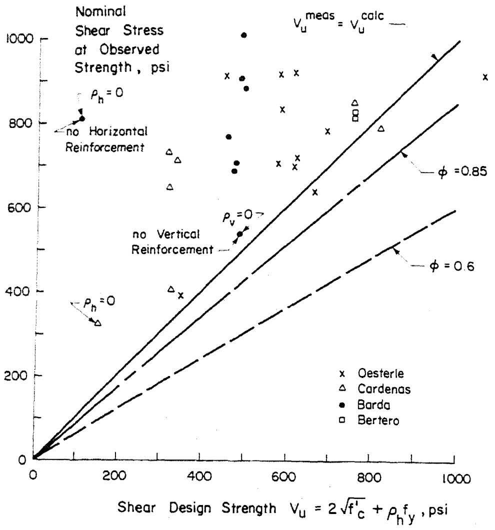

Fig. 6 Measured vs. Design Shear Capacity

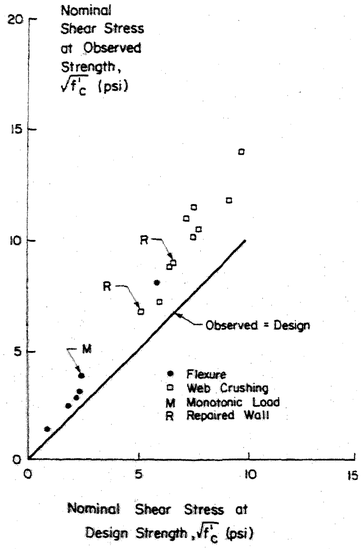

Fig. 5 Measured vs. Design Flexural Capacity

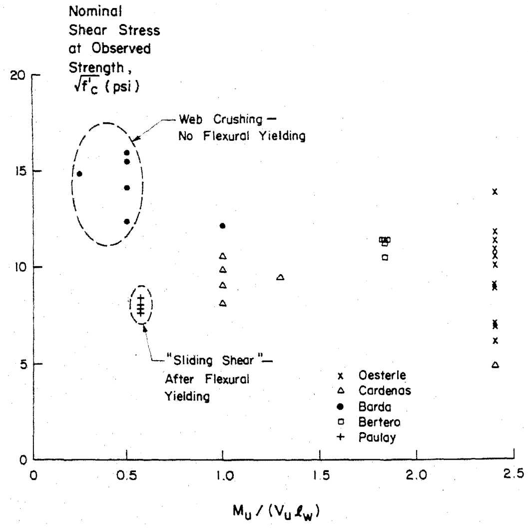

Fig. 7 Measured Shear Strength vs. Moment-to-Shear Ratio