DESIGN OF EARTHQUAKE-RESISTANT STRUCTURAL WALLS

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ABSTRACT

This paper describes results of research on earthquake-resistant walls and application of these results to design criteria. In particular, behavior of laboratory specimens during tests to destruction is described. Modes of response and damage, are then related to design considerations. The data are applicable to walls used as lateral load resisting elements for wind or earthquake forces.

INTRODUCTION

Reinforced concrete structural walls are frequently used in buildings to provide lateral resistance to earthquake forces. Performance of structural walls subjected to earthquakes is a function of stiffness, strength, deformation capacity, and deformation demand. For certain structures, particularly tall buildings in regions of high seismic risk, it may not be practical to design lateral load resisting walls to remain elastic. 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 results of research on seismic behavior of reinforced concrete walls. In particular, behavior of laboratory specimens during tests to destruction is described. Variables that influence strength and deformation capacity are discussed. Modes of response and damage are related to design considerations for adequate flexure, shear and deformation capacity.

EXPERIMENTAL RESULTS

Experimental Programs

In the past decade, a number of experimental programs to investigate behavior of walls have been conducted. Data from several of these programs (1,2,3,4,5) are used in this paper. However, discussion is primarily based on data from an experimental program conducted at the

Portland Cement Association (PCA).(3)

The PCA test program 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. Specimens were 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.

Observed Behavior and Modes of Failure

The following presents a description of observed general behavior and failure mechanisms. It should be noted that damage levels observed in laboratory tests provide a means of evaluating the "final" mechanism of resistance of the structure. For tests simulating seismic conditions, specimens are generally subjected to inelastic load cycles well in excess of what might reasonably be expected in a severe earthquake. Test results should be evaluated within this context.

Behavior of walls subjected to load reversals is related to the magnitude of applied shear stresses. Walls subjected to relatively low maximum nominal shear stresses of $3.0 \sqrt{f'_c}$ (psi) or less behave differently than walls subjected to relatively high maximum shear stresses of $7.0 \sqrt{f'_c}$ (psi) or greater.

Behavior of walls subjected to low nominal shear stress is characterized by the formation of a predominantly horizontal crack pattern in the lower region of the wall after a few inelastic reversals. This pattern is shown in Fig. 4(a). Therefore, after yield of vertical steel, stresses are predominantly transferred by interface shear across horizontal cracks. Capacity of this shear transfer mechanism is adequate to develop a flexural failure mode. Bar fracture precipitated by prior "inelastic" bar buckling, instability in the compression zone, or concrete crushing are final failure modes for such walls. These failure modes are shown in Fig. 5(a), (b), and (c).

Behavior of walls subjected to high nominal shear stress is characterized by development of inclined cracks crisscrossing the web to form relatively symmetrical compression strut systems for each direction of loading. This pattern is shown in Fig. 4(b). A major portion of the shear transfer mechanism is truss action. Truss action provides a stiffer system than that for walls exhibiting flexural type behavior. Capacity is generally limited by web crushing as shown in Fig. 5(d.) However, diagonal tension failure as shown in Fig. 5(e) is possible if capacity of horizontal reinforcement is exceeded.

A wall in which capacity was limited by "sliding shear" is shown in Fig. 5f. Sliding shear occurs under increasing numbers of inelastic load reversals as interface shear transfer along cracks in walls deteriorate. Sliding shear response is a function of the attainment of flexural yielding, number of load reversals, level of axial load, and crack pattern that develops. If cracks from load reversals intersect to form primarily horizontal planes, shear transfer across planes can be lost after a large number of inelastic cycles.

Effects of Program Variables

The following is a discussion of effects of variables that affect behavior and capacity of walls.

Load History - 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.(6)

Figure 6 shows data on measured and calculated flexural capacities. calculated capacities represent monotonic flexural strength. As can be seen in Fig. 6 walls subjected to monotonic load (denoted by the letter M) have measured capacities that are close to calculated capacities. For walls subjected to inelastic load reversals, flexural capacities can be up to 15% less than monotonic flexural capacities.

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 (5) 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.

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 8 shows the relationship between design strength and actual measured strength. Present designs may underestimate 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 can 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.(1) 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.(1) 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 9 gives a comparison between measured wall shear capacities and design values. 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. 9, 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.(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.(3)

Diagonal Reinforcement - Use of a diagonal reinforcement in webs of structural walls has been proposed to reduce shear distortions and resist sliding shear.(5,7) Wall tests have shown improved hysteretic response with use of diagonal reinforcement.(6,8) Properly designed and detailed diagonal reinforcement provides a system with increased energy dissipation capacity.

Because diagonal reinforcement is more complex to place than conventional orthogonal reinforcement, use of diagonal bars is generally warranted only when anticipated energy dissipation demands (numerous inelastic cycles) are severe.

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 (9) demonstrate that, in addition to providing confinement to increase concrete strain capacity, transverse reinforcement serves the following primary functions:(3)

(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 the other functions of special transverse reinforcement 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 for walls built in regions of high seismicity. Special transverse reinforcement is only needed in wall sections where concentrated inelastic rotations are expected.

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 (3) have shown that web crushing is dependent upon both strength and deformation levels.

Section Shape - Wall tests have included three basic section shapes identified as rectangular, barbell, and flanged.(1-5) 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 compression zone under severe load reversals.(3,6)

The barbell shaped section represents a wall between two column lines. Column boundary elements provide relatively large in and out-of-plane stiffness. These elements limit sliding shear by acting as large dowels. Since the 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. 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 compression boundary element to "shear through" after web crushing.

Axial Compressive Stress - For walls loaded monotonically, axial compressive stress has been found to increase moment capacity and reduce ultimate curvature.(1) Comparison of results for wall specimens subjected to reversing loads indicates that axial load increases moment and shear capacity.(3,6) 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.

SUMMARY AND CONCLUSIONS

Limits on Flexural Capacity

Three limits on flexural capacity of walls have been observed in tests. These include bar fracture, crushing of concrete in the compression zone, and lateral instability of the compression zone.

Bar fractures were precipitated by severe inelastic load reversals that caused alternate tensile yielding and compressive buckling of reinforcement. This yielding and subsequent buckling caused fracture of the bars at stresses approximately 15% lower than those reached for monotonic loading. Special transverse bars around vertical reinforcement are effective in delaying buckling. However, benefits of special reinforcement were only observed after specimens were loaded to deformation levels beyond what might reasonably be expected in a severe earthquake.

For slender rectangular walls with a high percentage of vertical reinforcement and significant axial compressive stress, crushing of the compression zone can occur. This mode is also important for unsymmetrical sections such as a T-shape that occurs at intersecting walls. The "stem" of the T-shape can be heavily stressed under load reversals.

In design, vertical reinforcement ratios in boundary elements are limited to avoid concrete crushing. In addition, special transverse reinforcement provides increased strain capacity of the concrete.

Flexural capacity of rectangular walls may also be limited by out-of-plane instability of the compressive zone. This can occur under severe inelastic reversals. Limits on design thickness of walls are used to avoid this type of response.

Limits on Shear Capacity

For walls with maximum nominal shear stresses lower than $3\sqrt{f'_c}$ (psi) no problems with shear transfer were observed. For walls subjected to higher nominal shear stresses, capacities may be limited by diagonal tension, sliding shear, or web crushing.

Tests indicate current ACI code provisions for shear design of walls are adequate to prevent diagonal tension failures.

Sliding shear response is a function of the attainment of flexural yielding, number of load reversals, level of axial load, and crack pattern that develops. It can be anticipated in the range of nominal shear stress of $3\sqrt{f'_c}$ to $7\sqrt{f'_c}$ (psi). If cracks that develop under reversals intersect to form primarily horizontal planes, it is possible that shear transfer across planes can be lost after a large number of inelastic cycles. Vertical boundary elements function as large dowels that aid horizontal shear transfer and resist sliding shear. As another approach, use of diagonal reinforcement has been suggested.(7)

For walls developing inclined cracks under reversals, wall capacity may be reached as diagonal struts in the web crush. Web crushing capacity has been found to be a function of concrete compressive strength and maximum shear distortions applied to the wall. 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%.(10)

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

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

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

Comments on Deformation Capacity

Much of the work on evaluation of design criteria and detailing for earthquake-resistant structures is based on laboratory tests using simulated load histories. Little work has been done on evaluating the extent to which deformation demands imposed in the laboratory relate to those imposed during actual earthquakes.

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 readily meet the drift criteria. 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.

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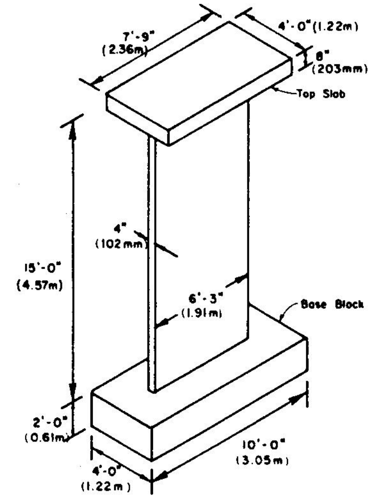
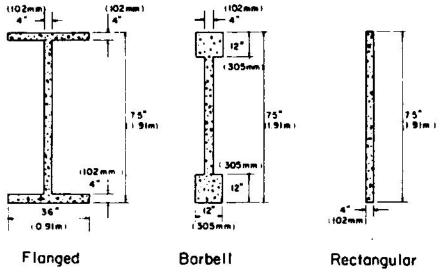


Fig. 1 Test Specimen



Flanged Barbell Rectangular

Fig. 2 Cross-Sections

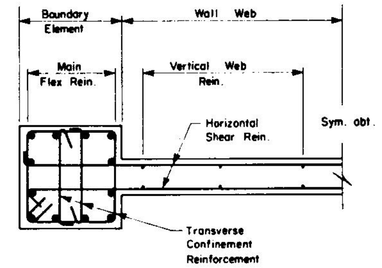


Fig. 3 Wall Section

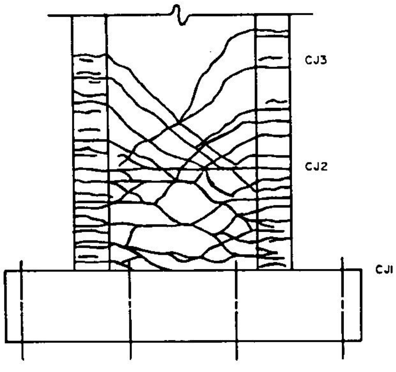


Fig. 4(a) Wall Subjected to Low Nominal Shear Stress

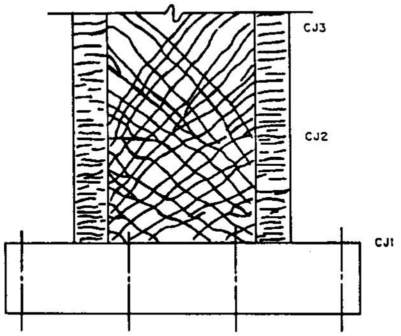
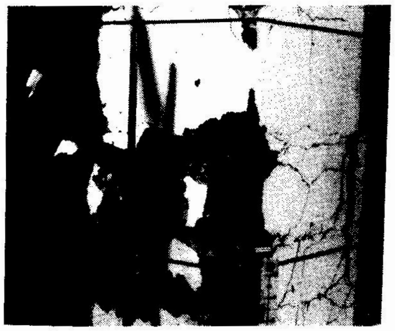
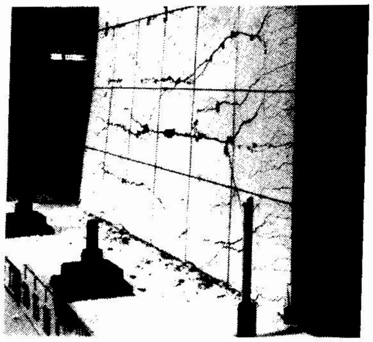


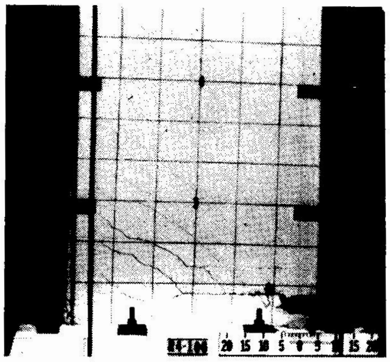
Fig. 4(b) Wall Subjected to High Nominal Shear Stress



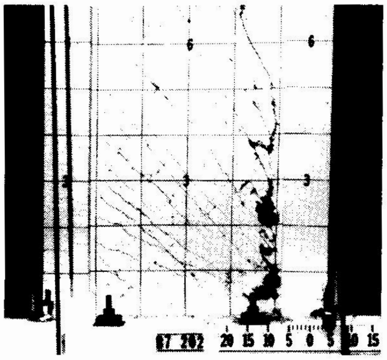
5(a) "Inelastic" Bar Buckling



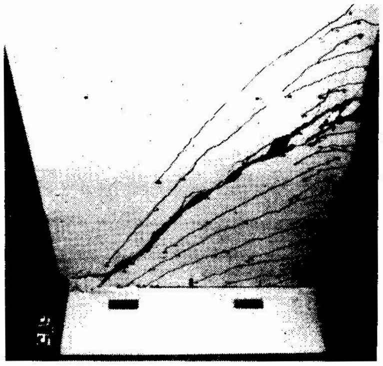
5(b) Instability of Compression Zone



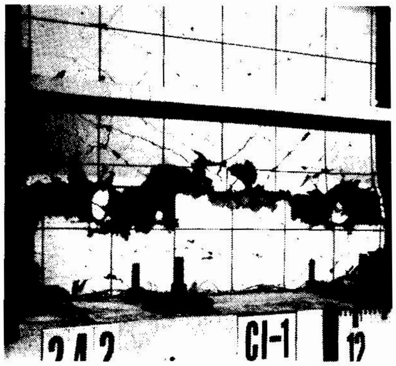
5(c) Crushing of Compression Zone



5(d) Web Crushing



5(e) Diagonal Tension



5(f) Sliding Shear

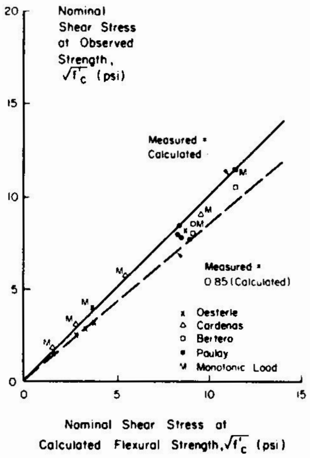


Fig. 6 Measured vs. Calculated Flexural Capacity

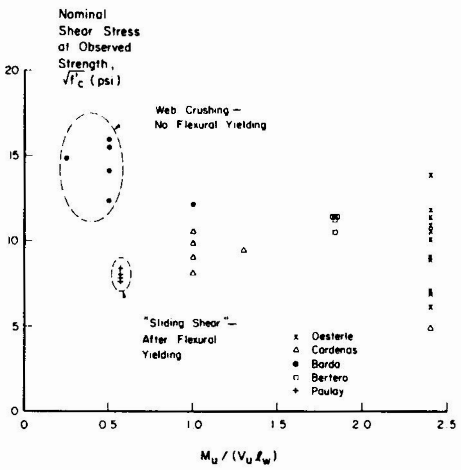


Fig. 7 Measured Shear Strength vs. Moment-to-Shear Ratio

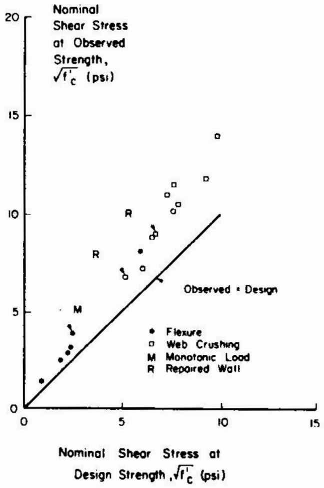


Fig. 8 Measured vs. Design Flexural Capacity

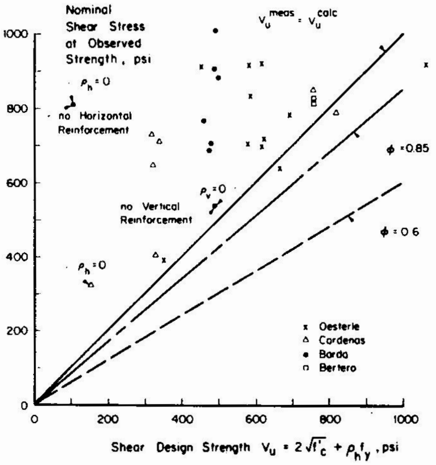


Fig. 9 Measured vs. Design Shear Capacity