DUCTILITY OF STRUCTURAL WALLS FOR DESIGN OF EARTHQUAKE RESISTANT BUILDINGS

by

A. E. Fiorato, R. G. Oesterle, and W. G. Corley[1]

SYNOPSIS

Tests of nine reinforced concrete specimens representing walls for lateral bracing in earthquake-resistant buildings are described. The model walls were 4.57m high and 1.91m wide. Wall thicknesses were 102mm. Specimens were subjected to in-plane horizontal reversing loads.

Controlled variables included the shape of the wall cross section, the amount of main flexural reinforcement, and the amount of hoop reinforcement around the main flexural reinforcement. In addition, one wall was subjected to monotonic loading. A test of a repaired wall is also described. Results, including strength and ductility, are given for the walls.

NOTATION

f'_c = compressive strength of standard 152x305mm concrete cylinders

h = overall thickness of wall

ℓ_w = horizontal length of wall

V = total applied shear force

ρ_f = ratio of main flexural reinforcement area to gross concrete area of boundary element.

ρ_h = ratio of horizontal shear reinforcement area to gross concrete area of a vertical section of wall web.

ρ_n = ratio of vertical web reinforcement area to gross concrete area of a horizontal section of wall web.

ρ_s = ratio of effective volume of confinement reinforcement to the volume of core in accordance with Eq. (A.4) of ACI 318-71(1).

INTRODUCTION

As part of an experimental and analytical investigation of structural walls for earthquake resistant buildings, large isolated reinforced concrete walls are being subjected to reversing in-plane lateral loads. The project is supported in part by NSF-RANN Grant GI-43880.

The primary objective of this investigation is to develop structural walls with adequate strength and energy dissipation capacity for earthquake resistant structures.

---

[1]Respectively, Senior Structural Engineer, Associate Structural Engineer, Structural Development Section, and Director, Engineering Development Department, Portland Cement Association, Skokie, Illinois, U.S.A.

In this paper, the strength and ductility of the test specimens are discussed. The specimens represent approximately 1/3-scale models of full-size walls, although no specific prototype walls were modeled. The controlled variables in the program include the shape of the wall cross section, the amount of main flexural reinforcement, and the amount of hoop reinforcement around the main flexural reinforcement. Table 1 provides a summary of the test program.

TEST PROGRAM

Dimensions of the test specimens are shown in Fig. 1. Flanged, barbell, and rectangular cross sections have been investigated. Nominal cross sectional dimensions of these sections are shown in Fig. 2.

In proportioning the walls, the design moment was calculated following procedures in the ACI Building Code(1). Strain hardening of the steel was neglected. Horizontal shear reinforcement was provided so that the calculated design moment would be developed. Shear reinforcement was provided to satisfy the ACI Building Code(1). Design yield stress of the steel was 414 MPa and design concrete strength was 41.4 MPa.

The test specimens were constructed in six vertical lifts. Figure 3 shows the reinforcing details used in one of the walls. Specimens B3, R2, B4, and B5 were constructed with confinement reinforcement in the lower 1.83m of the boundary elements. For rectangular sections, the "boundary element" was taken to extend 190mm from each end of the wall.

Specimen B5R was a retest of Specimen B5. Following the test of B5, the wall was placed in a vertical position. Then the damaged web concrete was removed up to a height of about 2.74m. New web concrete was cast in three lifts. The columns were repaired with a surface coating of neat cement paste.

The apparatus for testing the walls is shown in Fig. 4. Each specimen was loaded as a vertical cantilever with forces applied through the top slab. The test specimens were loaded in a series of increments. Each increment consisted of three complete reversed cycles. About three increments of force were applied prior to initial yielding. Subsequent to initial yielding, loading was controlled by deflections in 25mm increments. A more detailed description of the experimental program is given elsewhere(2).

OBSERVED LOADS

Yield and maximum loads observed during the tests are listed in Table 1. Values are given for the force and for the corresponding nominal shear stress. The yield loads are those applied when all flexural reinforcement in the boundary element reached yield. In Table 1 design strengths are listed. These were calculated following the 1971 ACI Building Code(1) requirements, but considering the capacity reduction factors $\phi = 1.0$. The observed loads for all specimens exceeded calculated ACI design strengths.

Specimens F1, B2, B5, and B5R developed high nominal shear stresses. The failure mode for these walls was associated with web shear distress. Specimen B5 was similar to B2 except that confinement reinforcement was provided in each column of B5. The capacity of B5 was 22% greater than that of B2. Specimen B5R, the repaired wall, had about the same capacity and failure mode as the original wall B5. However, B5 was initally stiffer than B5R.

Specimens Bl, Rl, B3 and R2 developed low nominal shear stresses. For these specimens, damage to the boundary elements increased as alternate tensile yielding and compressive buckling of the main tensile reinforcement occurred. Eventually, the main reinforcing bars fractured. The fractures were influenced by bar buckling. Loss of load capacity in these specimens was gradual as bars fractured and as broken concrete pieces in the boundary elements were lost.

Specimen B3 was similar to Bl except for the addition of confinement reinforcement in each boundary element of B3. In contrast to the strength difference observed between B2 and B5, Specimens Bl and B3 had about the same load capacity.

Wall B3, loaded cyclically, reached 80% of the capacity of the companion wall, B4, that was monotonically loaded.

LOAD VERSUS DEFLECTION ENVELOPES

Load versus deflection envelopes for all specimens are shown in Fig. 5. The deflection is that at the top of the specimen. The envelope for each curve was obtained by passing lines through the peak points of each new maximum loading cycle.

DUCTILITY

The ductility of a structure is commonly used as a measure of its post-yield deformation capacity. Ductility is often defined as the ratio of a specified deformation at a particular load to that at yield. The use of ductility ratios in seismic design implies certain limitations that are discussed by Paulay and Uzumeri(3). In this paper, the top deflection ductility ratio is used for comparison of specimens.

Figure 6 shows the cumulative top deflection ductility ratio(4,5) versus load for each specimen. The yield deflection is that at yield of all flexural reinforcement in the boundary element. From the inset in Fig. 6, it should be apparent that the ductility ratio is very sensitive to the definition of the yield deflection.

Comparison of Specimens Bl and B3 in Fig. 6 shows the beneficial effects of confinement reinforcement on ductility for walls that failed in the flexural mode. Confinement hoops in B3 helped to limit, but did not prevent bar buckling. The hoops in B3 were spaced at 2.7 times the diameter of the main vertical bars. For walls that failed in shear, B2 and B5, no increase in ductility as a result of confinement hoops was observed. However, the boundary elements of B5 were in much better condition for repair at the end of the test.

Figure 6 indicates the larger ductilities obtained for all walls subjected to low shear. This would be expected because design of Specimens Fl, B2, and B5 permitted shear failures. Even the walls that failed in shear exhibited post-yield deflection capabilities. In any case, the ductility must be evaluated in terms of what is required as well as what can be attained.

CONCLUSIONS

The following observations are based on the test results:

1. All specimens had a capacity greater than that indicated by the strength provisions of the 1971 ACI Building Code(1).

2. A specimen subjected to 25 inelastic cycles reached 80% of the capacity of a companion specimen that was monotonically loaded.

3. Lateral confinement hoops added around the main flexural reinforcement in the boundary element had no apparent effect on the capacity of a wall limited by flexural strength. Addition of confinement hoops resulted in a 22% increase in capacity for a wall limited by shear strength.

4. Addition of confinement hoops nearly doubled the cumulative top dispacement ductility ratio for a wall limited by flexural strength. Addition of confinement hoops had no significant effect on ductility of a wall limited by shear strength.

5. All specimens exhibited substantial post-yield deflections under reversing load.

6. Repair of a specimen by recasting the web concrete provided a wall with essentially the same capacity, but with a lower initial stiffness. Strengths of both the original and the repaired wall were limited by web crushing.

BIBLIOGRAPHY

1. "Building Code Requirements for Reinforced Concrete (ACI 318-71)", American Concrete Institute, Detroit, 78 pp.

2. Fiorato, A. E., Oesterle, R. G. Jr., and Carpenter, J. E., "Reversing Load Tests of Five Isolated Structural Walls," International Symposium on Earthquake Structural Engineering, St. Louis, 1976.

3. Paulay, T. and Uzumeri, M., "A Critical Review of the Sesmic Design Provisions for Ductile Shear Walls of the Canadian Code and Commentary," Canadian Journal of Civil Engineering, Vol 2, No. 4, 1975, pp. 592-601.

4. Hanson, N. W. and Conner, H. W., "Seismic Resistance of Reinforced Concrete Beam-Column Joints," Journal of the Structural Division, ASCE, Vol. 93, No. ST5, October 1967, pp. 533-560.

5. Paulay, T. and Santhakumar, A. R., "Ductile Behavior of Coupled Shear Walls," Journal of the Structural Division, ASCE, Vol. 102, No. ST1, Jan. 1976. pp. 93-108.

PCA R/D Ser. 1555

TABLE 1 - TEST PROGRAM

Speci-men	Shape	Reinforcement(1)				Conc.	ACI Design Strength				Observed Loads			
							Flexural		Shear		Full Yield		Maximum	
		ρ_f (%)	ρ_h (%)	ρ_n (%)	ρ_s (%)	f'_c (Mpa)	kN	$\sqrt{f'_c}$	kN	$\sqrt{f'_c}$	kN	$\sqrt{f'_c}$	kN	$\sqrt{f'_c}$
F1		3.89	0.71	0.30	-	38.4	645	0.67	625	0.65	670	0.70	835	0.87
R1(4)		1.47	0.31	0.25	-	44.8	80	0.07	365	0.35	95	0.09	120	0.12
R2(4)		4.00	0.31	0.25	2.07	46.5	155	0.15	365	0.35	185	0.17	215	0.21
B1(4)		1.11	0.31	0.29	-	53.0	205	0.18	365	0.32	225	0.20	270	0.24
B3(4)		1.11	0.31	0.29	1.28	47.3	205	0.19	365	0.34	230	0.22	275	0.26
B4(2,4)		1.11	0.31	0.29	1.28	45.0	205	0.20	365	0.35	245	0.23	335	0.32
B2		3.67	0.63	0.29	-	53.6	575	0.51	565	0.50	570	0.50	680	0.60
B5		3.67	0.63	0.29	1.35	45.3	575	0.55	565	0.54	615	0.59	760	0.73
B5R(3)		3.67	0.63	0.29	1.35	42.5	575	0.56	565	0.56	-	-	745	0.74

(1) All Reinforcement 414 MPa yield stress

(2) Monotonic Loading

(3) Repaired Specimen

(4) Shear reinforcement goverened by maximum bar spacing requirements

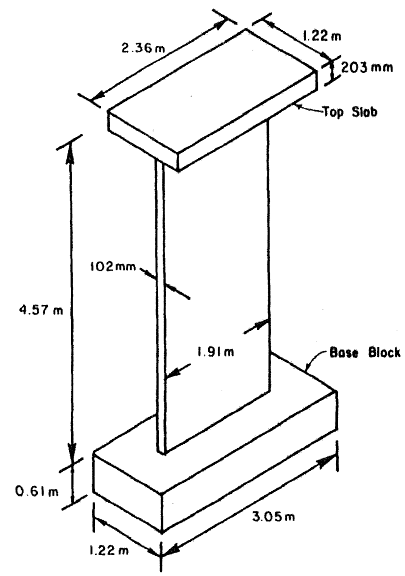

Fig. 1 Nominal Dimensions of Test Specimen with Rectangular Cross Section

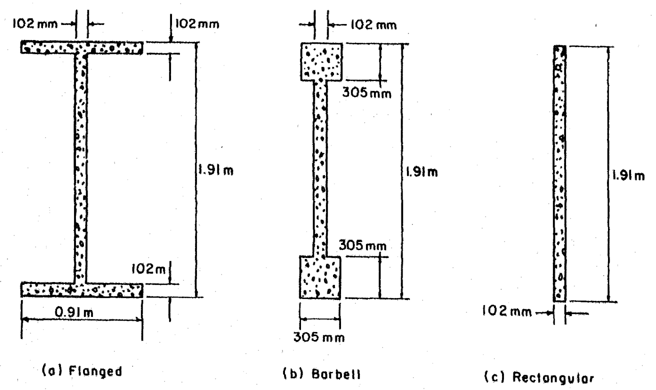

Fig. 2 Nominal Cross-Sectional Dimensions of Test Specimens

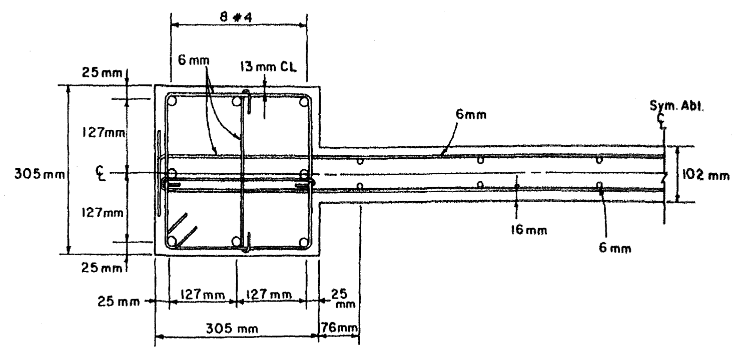

Fig. 3 Cross Section of Specimen B3

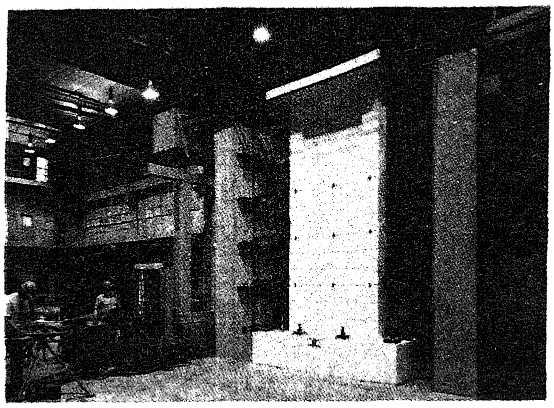

Fig. 4 Isolated Wall Test Setup

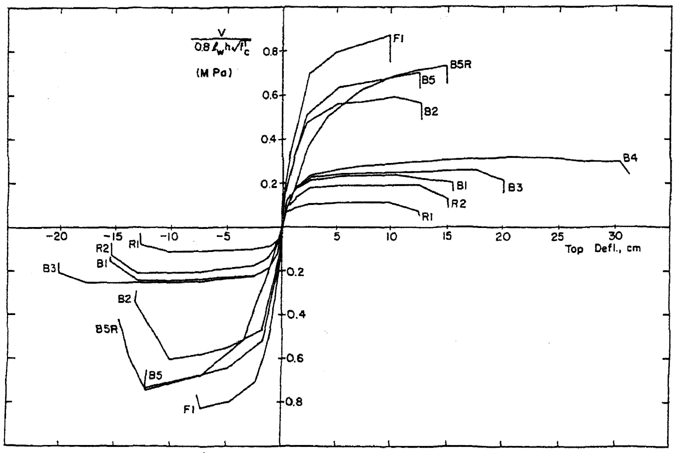

Fig. 5 Load Versus Deflection Envelopes

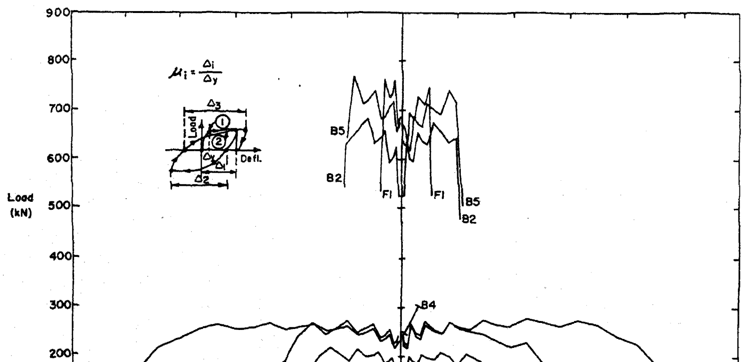

Fig. 6 Load Versus Cumulative Ductility