DEVELOPMENT OF REINFORCEMENT DETAILS TO IMPROVE THE CYCLIC RESPONSE OF SLENDER STRUCTURAL WALLS

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SUMMARY

A series of four reinforced concrete walls were tested to failure to evaluate the influence of diagonal web reinforcement on the hysteretic response. Two walls contained conventional horizontal and vertical web reinforcement and two walls contained inclined reinforcement. Reinforcement details were representative of construction practice in regions of low to moderate seismic risk. A single layer of web reinforcement was used and the transverse reinforcement in the boundary elements did not confine the concrete core.

Both walls with conventional web reinforcement failed due to web crushing. Pinched shapes characterized the hysteresis curves for top displacement and shear distortion near the base. In contrast, the walls with diagonal reinforcement displayed rounded hysteresis curves, and failed due to crushing of the boundary elements. The choice of web reinforcement did not have a significant influence on the maximum lateral load resisted by the walls, but measured crack widths were less, and more energy was dissipated by the walls with diagonal reinforcement during loading cycles to comparable levels of displacement.

INTRODUCTION

Fundamental studies of the behavior of slender reinforced concrete structural walls were conducted during the 1970s at the Portland Cement Association [Oesterle, et al, 1976, and Oesterle, et al, 1979]. Experimental parameters included the amounts of longitudinal, web, and confinement reinforcement. The results of these tests were used to establish reinforcement requirements in current building codes [ACI 318, 1995], and were later interpreted to investigate the influence of the amount of reinforcement on wall behavior [Wood, 1991]. Subsequent analytical studies [Sittipunt and Wood, 1995] indicated that the hysteretic response of walls susceptible to shear failures could be improved if diagonal reinforcement was used in the web. Diagonal web reinforcement provided a more effective mechanism for transferring lateral forces into the foundation and resulted in lower shear strains near the base of the wall and improved energy dissipation characteristics.

Experience during the 1989 Loma Prieta and 1994 Northridge earthquakes has shown that economic losses can be significant in buildings that satisfied the life safety design criteria inherent to current building codes. As a result, procedures to consider the post-earthquake condition of a building when establishing design limit states are currently being developed. Diagonal web reinforcement in structural walls appears to be one way to control structural damage using conventional methods of construction. The results of an experimental investigation comparing the hysteretic response of walls with conventional and diagonal web reinforcement are described in this paper.

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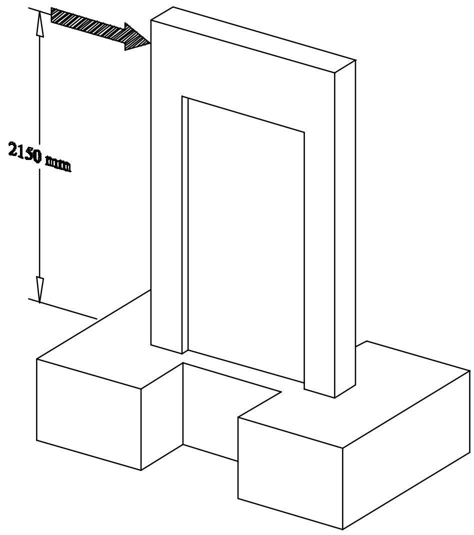
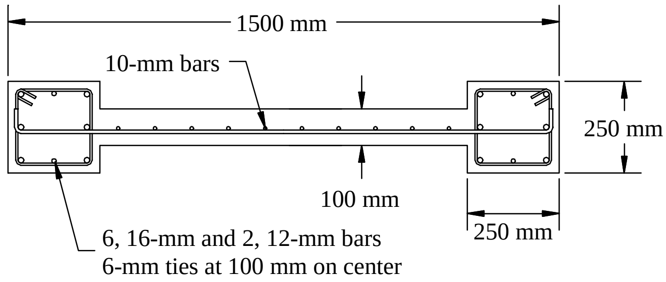


(a) Overview of Test Setup



(b) Cross-Sectional Dimensions

Figure 1: Dimensions of Test Specimens

EXPERIMENTAL PROGRAM

Four reinforced concrete wall specimens were constructed and tested at Chulalongkorn University to investigate the influence of diagonal web reinforcement on the hysteric response of structural walls. The dimensions of the specimens are shown in Figure 1. All walls had a barbell-shaped cross section with a web thickness of 100 mm and 250 by 250-mm boundary elements. The overall length of the cross section was 1500 mm. Vertical reinforcement was anchored in a 600-mm thick base girder that was bolted to the laboratory floor. A 250-mm wide by 500-mm deep beam was cast on top of the wall panel, and a hydraulic actuator was attached to the specimen at mid-depth of the beam. Lateral loads were applied 2150 mm above the base of the wall.

The primary experimental parameters were the amount and orientation of the web reinforcement. The longitudinal and transverse reinforcement in the boundary elements was the same in all four specimens (Fig. 1b). The transverse reinforcement in the boundary elements was not intended to provide confinement of the concrete core. The amount of transverse reinforcement provided was consistent with current practice in Thailand and was approximately one-fifth that required in the U.S. in regions of high seismic risk. A single layer of web reinforcement was used in all walls. Specimens W1 and W2 were reinforced with conventional horizontal and vertical web reinforcement, while diagonal web reinforcement was used in specimens W3 and W4.

The design procedures in the American Concrete Institute Building Code [ACI 318, 1995] for regions of low and moderate seismic risk were used to proportion the walls. During design, the concrete compressive strength was assumed to be 29 MPa and the yield stress of the reinforcement was assumed to be 390 MPa. The measured strengths of the materials used to construct the walls exceeded these values and are summarized in Table 1.

The reinforcement in specimen W1 was selected such that the nominal shear and flexural strengths of the wall were the same. Horizontal web reinforcement was spaced at 150 mm on center, and vertical web reinforcement was spaced at 200 mm on center for specimen W1. Bar spacings were decreased to 100 mm for the horizontal reinforcement and 150 mm for the vertical reinforcement in specimen W2. This change in spacing had a negligible influence on the calculated flexural capacity, but increased the nominal shear strength by 25% relative to specimen W1. The spacing of the web reinforcement in specimens W3 and W4 was the same as the spacing of the horizontal web reinforcement in specimens W1 and W2, respectively (Table 1). However, the web reinforcement in specimens W3 and W4 was rotated 45 degrees with respect to the longitudinal axis of the wall. The nominal strengths of specimens W1 and W3 and specimens W2 and W4 were essentially the same. Nominal capacities calculated using the measured material properties are listed in Table 2.

During the tests, lateral displacements were measured at four locations over the height of the walls (450, 900, 1500, and 2100 mm above the base). In addition, the shear strains were estimated from the diagonal distortion of a 900-mm square located at the base of the wall.

Table 1: Material Properties and Reinforcement Ratios

	W1	W2	W3	W4
Concrete Compressive Strength, MPa	36.6	35.8	37.8	36.3
Horizontal Web Reinforcement*				
Spacing, mm	150	100	—	—
Reinforcement ratio, %	0.52	0.79	—	—
Vertical Web Reinforcement*				
Spacing, mm	200	150	—	—
Reinforcement ratio, %	0.39	0.52	—	—
Diagonal Web Reinforcement*				
Spacing, mm	—	—	150	100
Reinforcement ratio, %	—	—	0.52	0.79
Longitudinal Reinforcement in Boundary Elements†				
Area, mm^2	1430	1430	1430	1430
Reinforcement ratio, %	2.29	2.29	2.29	2.29
Transverse Reinforcement in Boundary Elements‡				
Spacing, mm	100	100	100	100

Notes:

* Single layer of 10-mm deformed bars, f_y = 450 MPa

† Six, 16-mm deformed bars, f_y = 473 MPa and two, 12-mm deformed bars, f_y = 425 MPa

‡ Single tie, 6-mm plain bars, f_y = 444 MPa

MEASURED RESPONSE

The cyclic loading history used to test the specimens may be divided into discrete stages, each comprising three complete cycles to a specified force or displacement level. During the first stage, the walls were pushed with a maximum force of ±200 kN, which corresponded to the nominal cracking load. In subsequent stages, the specimens were pushed to integer multiples of the observed yield displacement, beginning with a displacement ductility of 1 in the second stage. The maximum positive displacement resisted by each wall during the first five stages of loading is shown in Figure 2. Slight differences in the maximum displacements sustained by each wall were observed during the first four stages of loading. These variations increased in amplitude during subsequent loading stages. Testing continued until the lateral load capacity of each specimen was reduced by the abrupt failure of the web or boundary elements. Three of the four specimens were able to withstand three complete cycles to a displacement ductility of 4 before failure, while specimen W3 failed during the second cycle to this displacement level.

Continuous plots of load versus top displacement are shown in Figure 3. Significant differences may be observed between the hysteretic response of the walls with conventional web reinforcement (W1 and W2) and the walls with diagonal web reinforcement (W3 and W4). A pinched shape characterized the hysteresis curves for walls W1 and W2. Cracks in the lower portion of the wall did not close when the applied load was reduced to zero, leading to a large reduction in the stiffness of the wall at low levels of applied load. In contrast, the hysteresis curves for walls W3 and W4 exhibited a rounded shape and the effective stiffness did not depend on the magnitude of the applied load during an individual loading cycle. Hysteresis curves for shear distortion in the lower 900 mm of the web are plotted in Figure 4. These data also indicate appreciable improvements in the response due to the diagonal reinforcement.

Table 2: Calculated and Measured Capacity of Specimens

Specimen	Calculated per ACI 318-95		Observed Response		
	Flexural Capacity	Shear Capacity	Maximum Load	Load at Web Crushing	Mode of Failure
	kN	kN	kN	kN	
W1	496	482	491	351	Web Crushing
W2	515	621	608	350	Web Crushing
W3	518	485	569	—	Crushing of Boundary Element
W4	545	622	618	—	Crushing of Boundary Element

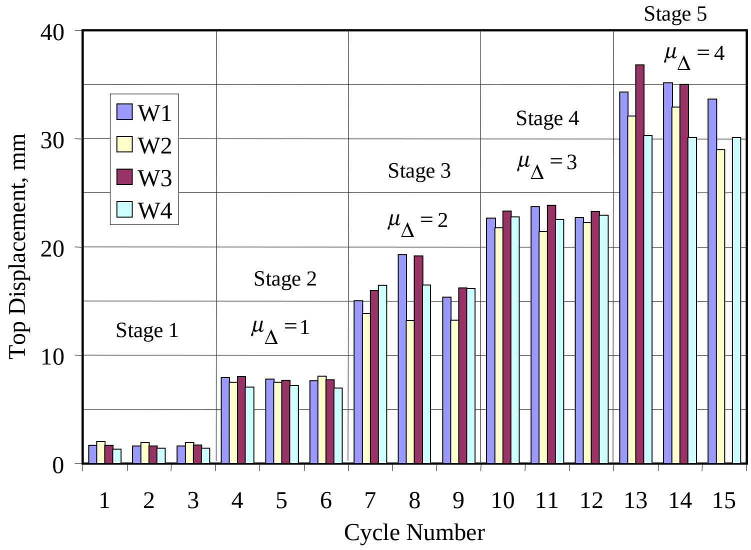


Figure 2: Maximum Positive Displacement Sustained during the First Five Stages of Loading

All four specimens sustained maximum loads that exceeded the calculated nominal capacities (Table 2). The walls with diagonal web reinforcement resisted higher loads than the companion walls with conventional reinforcement; however, the increase in strength was not significant for the walls with higher web reinforcement ratios. Walls W1 and W2 failed abruptly due to web crushing. The applied load at the onset of web crushing was approximately the same for the two specimens. This load was slightly more than 70% of the maximum load resisted by wall W1 and slightly less than 60% of the load resisted by wall W2. Similar reductions in shear strength with cycling have been observed in previous experimental investigations [Wolschlag, 1993]. Walls W3 and W4 failed when the concrete in the boundary elements crushed. This mode of failure was not unexpected, given the modest amount of transverse reinforcement in the boundary elements. Significant increases in the displacement capacities of walls were observed in previous tests when the amount of confinement reinforcement in the boundary elements was increased [Oesterle et al, 1976].

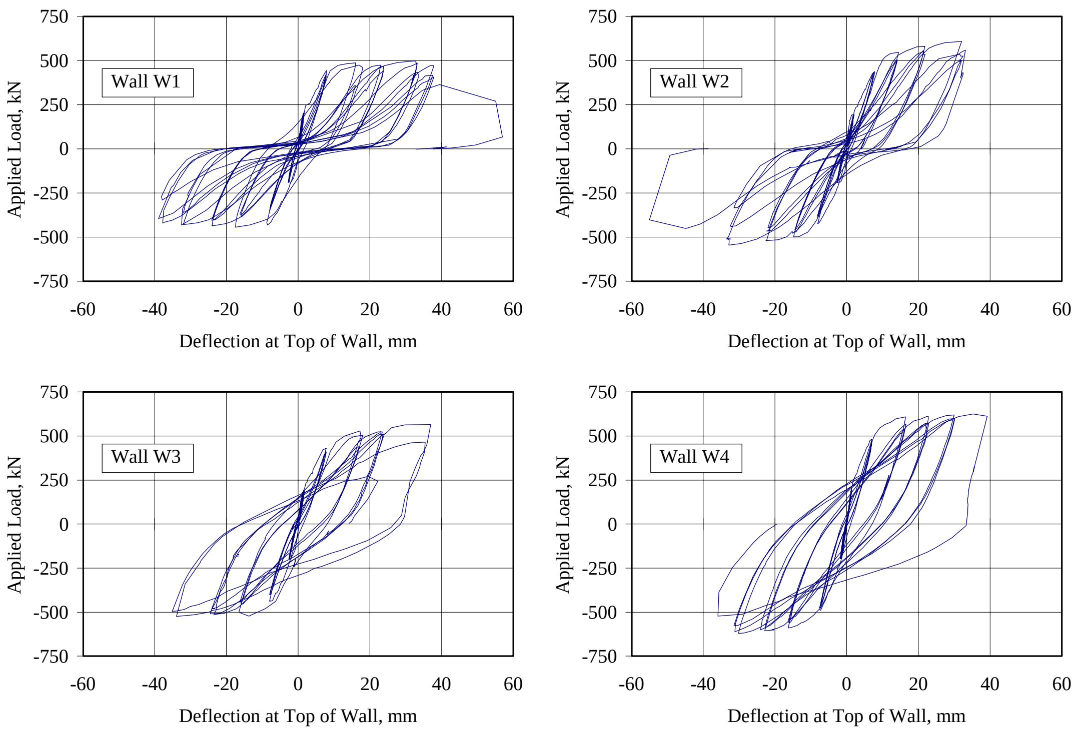


Figure 3: Load vs. Top Displacement

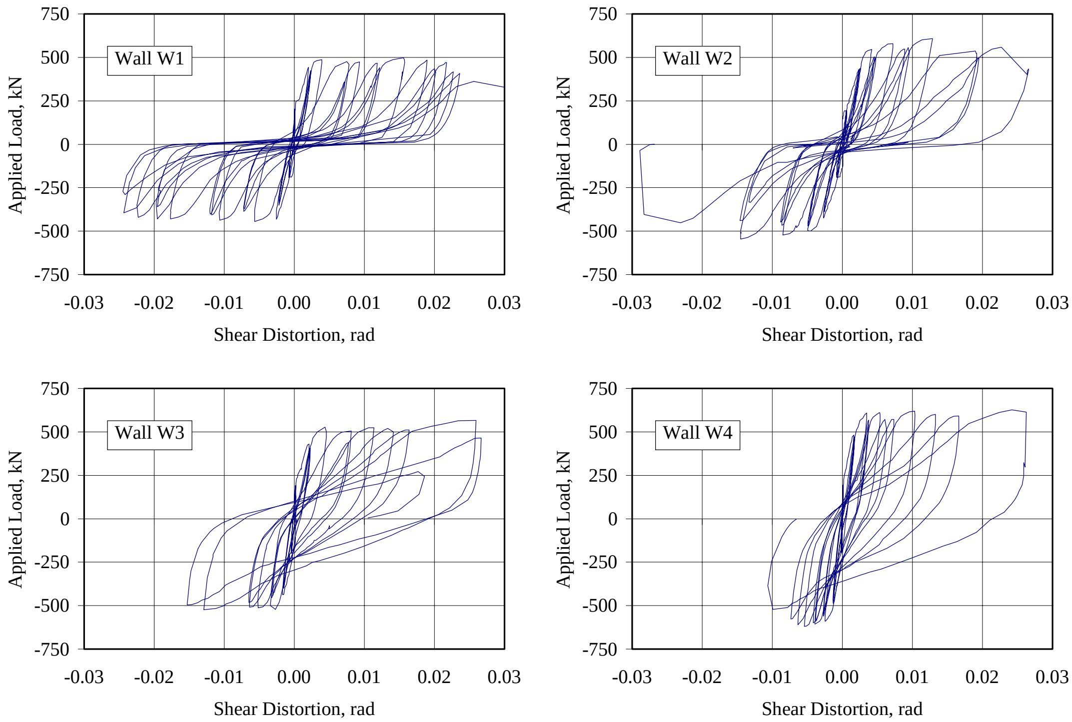


Figure 4: Load vs. Shear Distortion at the Base of the Web

Because the amplitudes of the imposed displacements were not the same for corresponding loading cycles for the four walls, normalized parameters were used to compare the energy dissipation characteristics of the walls. For each loading cycle, the maximum ductility ratio and the area enclosed by the overall hysteresis curves (Figure 3) were calculated. The accumulated ductility ratio was then defined as the maximum ductility ratio for a given cycle plus the sum of the maximum ductility ratios in all previous cycles. Similarly, the accumulated energy was a sum of the area enclosed by the hysteresis loops. These data are plotted in Figure 5 for loading stages 1 through 5. Accumulated energy increased nearly linearly with the accumulated ductility ratio for the four walls. The rate of increase was considerably higher for the walls with diagonal web reinforcement, indicating their ability to dissipate more energy at a given level of distortion. This confirms the qualitative observations based on the shape of the hysteresis curves.

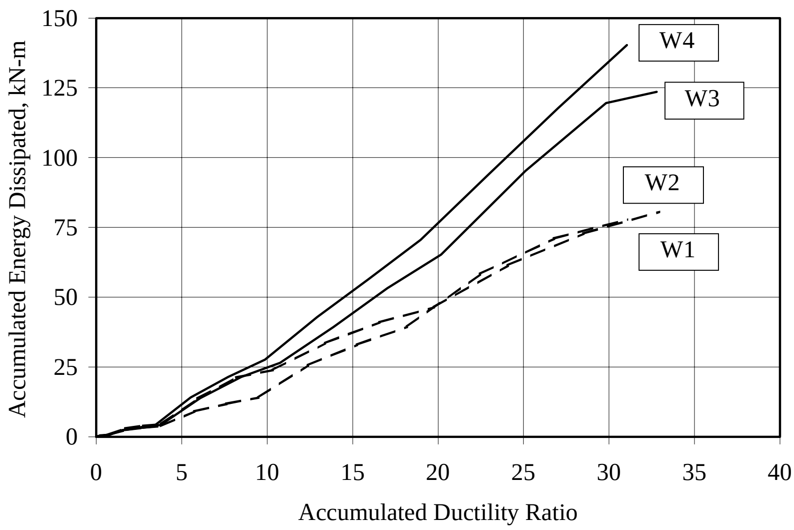


Figure 5: Energy Dissipated during the First Five Loading Cycles

CONCLUSION

The results of this experimental investigation have demonstrated that distributed diagonal web reinforcement is an effective means of improving the hysteretic response of structural walls. Because the diagonal web reinforcement crosses the paths of the cracks nearly perpendicularly, the reinforcement resists the applied loads in tension. In contrast, conventionally reinforced walls must rely on dowel action by the vertical steel and compressive struts in the concrete to transfer the applied loads into the foundation. The strength and stiffness of both of these mechanisms degrade with cycling, and these walls are susceptible to web crushing, a brittle mode of failure. While the capacities of walls W3 and W4 were also limited by the compressive strength of the concrete, previous research has shown that the response can be improved with additional confinement reinforcement in the boundary elements.

As engineers adopt performance-based design philosophies, new techniques must be developed to control structural damage reliably during earthquakes. Diagonal web reinforcement is one such approach. For loading cycles to a specified lateral displacement, walls with diagonal web reinforcement exhibit smaller crack widths and dissipate more energy than conventionally reinforced walls. In addition, with appropriate confinement of the boundary elements, brittle modes of failure can be avoided. These advantages in performance offset the difficulties associated with placement of diagonal bars during construction.

ACKNOWLEDGMENT

Funding for this project was provided by the Thailand Research Fund through a senior research scholar grant. Opinions and findings do not necessarily represent those of the sponsor. P. Lukkunaprasit and P. Pattararattanakul, former students at Chulalongkorn University, were responsible for construction and testing of the walls.

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