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SEISMIC PERFORMANCE OF SLENDER C-SHAPED WALLS SUBJECTED TO UNI- AND BI-DIRECTIONAL LOADING

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ABSTRACT

Reinforced concrete structural walls are common as the primary lateral load resisting system in modern mid- and high-rise buildings constructed in seismic regions, yet few research programs have investigated the seismic performance of modern, slender walls with nonplanar cross-sectional geometries. Three large-scale, C-shaped wall specimens, designed per ACI 318-08, were tested under uni- and bi-directional loading at the University of Illinois at Urbana-Champaign (UIUC). This paper presents experimental results including the cyclic load-deformation response and measured versus nominal flexural/shear strengths as well as a description of damage sequence. Final failure occurs due to a flexure-tension failure of boundary elements where multiple previously buckled bars fracture. From these tests, it is possible to conclude that with respect to uni- versus bi-directionally loading C-shaped walls have similar strong-axis load-deformation response until 0.75% drift as well as effective flexure/shear stiffness; however, there is a notable reduction in strong-axis ductility due to bi-directional loading. When comparing C-shaped walls to planar walls, the C-shaped specimens exhibit a more ductile flexural-tension controlled response where wall flanges contribute significantly to carrying compressive loads. Additionally, wall flanges and boundary elements are noted to be critical to resisting shear demands after the lightly-reinforced wall web has deteriorated.

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Seismic Performance of Slender C-shaped Walls Subjected to Uni- and Bi-directional Loading

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ABSTRACT

Reinforced concrete structural walls are common as the primary lateral load resisting system in modern mid- and high-rise buildings constructed in seismic regions, yet few research programs have investigated the seismic performance of modern, slender walls with nonplanar cross-sectional geometries. Three large-scale, C-shaped wall specimens, designed per ACI 318-08, were tested under uni- and bi-directional loading at the University of Illinois at Urbana-Champaign (UIUC). This paper presents experimental results including the cyclic load-deformation response and measured versus nominal flexural/shear strengths as well as a description of damage sequence. Final failure occurs due to a flexure-tension failure of boundary elements where multiple previously buckled bars fracture. From these tests, it is possible to conclude that with respect to uni- versus bi-directionally loading C-shaped walls have similar strong-axis load-deformation response until 0.75% drift as well as effective flexure/shear stiffness; however, there is a notable reduction in strong-axis ductility due to bi-directional loading. When comparing C-shaped walls to planar walls, the C-shaped specimens exhibit a more ductile flexural-tension controlled response where wall flanges contribute significantly to carrying compressive loads. Additionally, wall flanges and boundary elements are noted to be critical to resisting shear demands after the lightly-reinforced wall web has deteriorated.

Introduction

Reinforced concrete structural walls are common as the primary lateral load resisting system in modern mid- and high-rise buildings constructed in seismic regions. Flexurally-dominated walls are relatively stiff under service-level loading and are generally understood to exhibit a ductile behavior under severe earthquake loading. Though there is a heavy reliance on structural concrete walls by practicing engineers, few research programs have investigated the seismic performance of modern walls with nonplanar cross-sectional geometries. This deficiency inhibits the development of reliable performance-based earthquake engineering (PBEE) tools for structural walls. This paper summarizes a large-scale experimental test program conducted at the UIUC Network for Earthquake Engineering Simulation (NEES) lab focusing on slender walls with a C-shaped configuration frequently found in coupled-core systems.

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Description of Experiment

The three, nominally identical C-shaped wall specimens (CW1-3) were designed per ACI 318-08. These 1:3 scale walls simulate the bottom three floors of a ten-story prototype wall, resulting in a story height of 1.2 m (4 ft.), wall length of 3.0 m (10 ft.), flange length of 1.2 m (4 ft.), and wall thickness of 15 cm (6 in.). Fig. 1 shows the geometry and reinforcing for the walls; concrete strengths range 34.04-36.22 MPa (4937-5254 psi) and Grade 60 ASTM 706 steel was used.

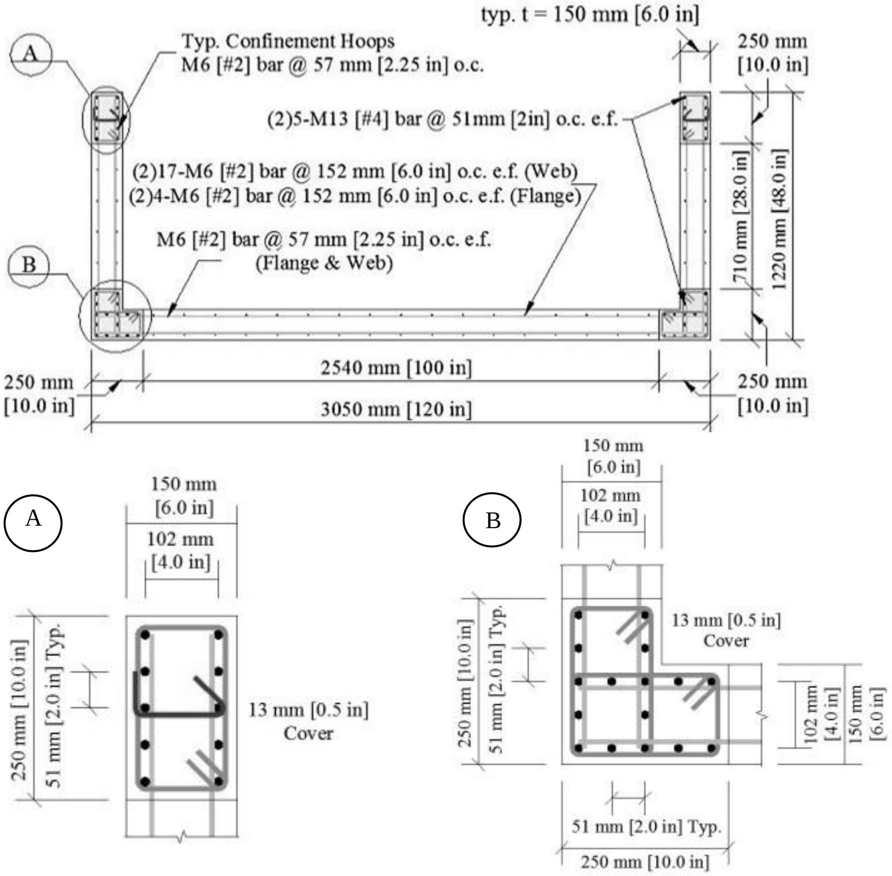

Figure 1. C-shaped wall specimens: geometry and reinforcing details.

The primary test parameter was loading direction: strong axis (CW1), strong + weak axis (CW2), strong + weak axis AND simulated coupling (CW3). In addition to cyclic displacement, walls were subject to overturning moment and axial load (typ. $0.05f_c'A_g$) to account for the upper seven stories not physically modelled. Test specimens were monitored with a dense, high-resolution sensor array; details about test setup, loading protocol, and instrumentation are in [1].

Experimental Results

Comprehensive datasets and support documentation for the C-shaped wall tests is available on the "Design Safe-CI" repository [2, 3, 4]; also, detailed discussion of wall response is in [1]. Fig. 2 shows the normalized base moment (ratio of measured base moment to calculated nominal moment, M_b/M_n) versus drift at the top of the wall for each wall. For bi-directionally loaded walls (CW2-3), plots include strong and weak-axis response. Note that for CW3, the weak-axis nominal moment, M_n, varies throughout the test due to the simulated coupling-action where the physical specimen is treated as the tension or compression pier and subject to variable axial load. Table 1 lists shear and moment demand versus capacities for each wall.

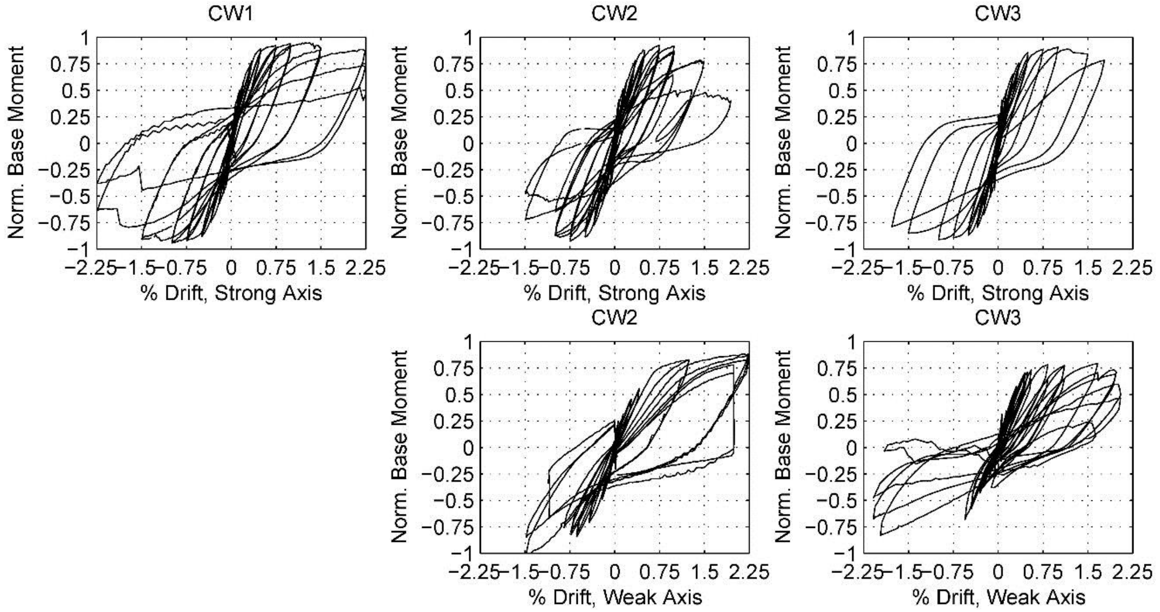

Figure 2. Normalized base moment versus third-story drift in strong and weak-axis directions.

Table 1. C-Shaped wall demands and capacities.

Loading Direction	**Wall ID**	**ACI shear strength, V_n (MPa)**	**Max shear demand, V_{max} (MPa)**	**V_{max} /V_n**	**Nominal flex. strength, M_n (kN m)**	**Max moment demand at base, M_{base} (kN m)**	**M_{base} /M_n**
Strong Axis	CW1	$0.48\sqrt{f'_c}A_g$	$0.21\sqrt{f'_c}A_g$	0.44	8,696	8,243	0.95
	CW2	$0.47\sqrt{f'_c}A_g$	$0.20\sqrt{f'_c}A_g$	0.42	8,712	8,066	0.93
	CW3	$0.47\sqrt{f'_c}A_g$	$0.20\sqrt{f'_c}A_g$	0.41	8,706	7,933	0.91
Weak axis, toe in tension	CW2	$0.41\sqrt{f'_c}A_g$	$0.05\sqrt{f'_c}A_g$	0.13	2,350	2,068	0.88
	CW3	$0.42\sqrt{f'_c}A_g$	$0.16\sqrt{f'_c}A_g$	0.38	2,777 ^{A}	2,187 ^{A}	0.79 ^{A}
Weak axis, toe in comp.	CW2	$0.41\sqrt{f'_c}A_g$	$0.09\sqrt{f'_c}A_g$	0.21	3,441	3,456	1.0
	CW3	$0.42\sqrt{f'_c}A_g$	$0.11\sqrt{f'_c}A_g$	0.27	2,328 ^{B}	1,944 ^{B}	0.84 ^{B}

^{A} Axial load = 3,318 kN compression
^{B} Axial load = 507 kN tension

All three C-Shaped walls have a similar damage sequence with nearly identical strong-axis response to nominal flexure strength. However, bi-directional loading resulted in substantial differences in the drift demands at the onset of the damage limit states as well as a significant reduction in stiffness during post-yield displacement cycles. Fig. 3 indicates typical damage/ cracking pattern of wall specimens at 1.5% drift. The damage mechanism of the walls is generally characterized by spalling and crushing of concrete along the wall-foundation interface due to sliding, loss of confinement in the boundary elements, and crushing of core concrete and severe buckling of longitudinal bars. Ultimately, the C-Shaped walls experience significant strength loss due to fracture of previously buckled boundary element bars, and thus can be characterized as having a buckling-rupture failure mechanisms. Further details available in [1].

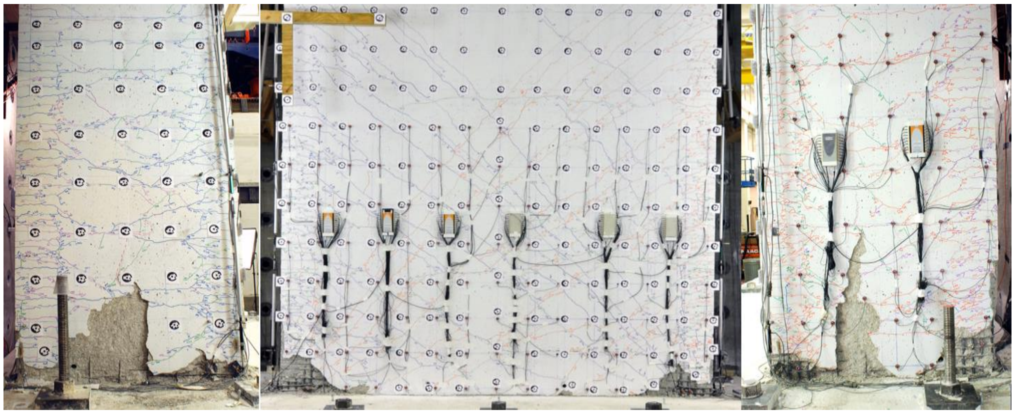

Figure 3. Damage to specimen CW2 at 1.5% X-drift.

Conclusions

From these tests, it is possible to conclude that with respect to uni- versus bi-directional loading C-shaped walls have similar strong-axis load-deformation response until 0.75% drift as well as effective flexure/shear stiffness; however, there is a notable reduction in strong-axis ductility due to bi-directional loading. When comparing C-shaped walls to planar walls, the C-shaped specimens exhibit a more ductile flexural-tension controlled response where wall flanges contribute significantly to carrying compressive loads. Additionally, wall flanges and boundary elements are noted to be critical to resisting shear demands after the lightly-reinforced wall web has deteriorated.

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