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Effect of web reinforcement on the seismic response of concrete squat walls reinforced with glass-FRP bars

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ABSTRACT

Six full-scale concrete squat walls reinforced with glass-fiber-reinforced-polymer (GFRP) bars were tested to failure under quasi-static reversed cyclic loading. Each test specimen measured 200 mm thick, 1500 mm long, and 2000 mm high. The test parameters were the configuration of web reinforcement (horizontal and/or vertical) and the horizontal web reinforcement ratio. The test specimens experienced different mode of failures as a function of the web reinforcement. The horizontal web reinforcement was found to significantly increase the ultimate load capacity as long as the failure was dominated by diagonal tension. It had no significant effect when the amount of horizontal web reinforcement provided was greater than what was needed for flexural resistance. Both horizontal and vertical web reinforcement was shown to be essential for crack recovery between load reversals and for controlling shear crack width as well as for enhancing the concrete contribution to the lateral shear resistance.

1. Introduction

Reinforced-concrete (RC) structural walls are one of the most common lateral load systems for buildings in regions prone to earthquake. A large proportion of the walls constructed in North America can be classified as squat walls with a wall height-to-length ratio (h_w/l_w) typically less than 2.0 (Fig. 1). There are different types of structural systems represented by squat walls. Most industrial and nuclear facilities rely on reinforced-concrete squat walls as their primary seismic lateral-force-resisting components. The behavior of reinforced squat walls is different from that of slender walls (walls with a height-to-length ratio greater than 2.0) due to their relatively larger magnitude of shearing and normal stresses. Test investigations have revealed that, by the onset of flexural reinforcement yielding, shear deformations—either shear distortion and/or sliding—are activated (Fig. 2). The shear deformations were shown to be mobilized along the yielding zone and dominate the behavior which cause rapid load and stiffness degradation with subsequent premature shear failure [1,2].

A considerable amount of experimental and analytical work has been devoted to study the behavior of steel-reinforced squat walls. The investigations focused on a broad spectrum of topics and loading procedures covering the material and component levels with the aim of providing prescriptive design recommendations for seismic design codes. Nevertheless, due to the stiff nature of squat walls and the discrepancy in testing methodologies, various research groups have conflicting positions on many aspects. An important one is the impact of web reinforcement on shear strength. Currently, there is no consensus among researchers about the influence of web reinforcement in squat walls shear strength. Some researchers have reported that using proper amount of horizontal reinforcement restrained the diagonal tension, thereby increasing the shear strength [3]. In contrast, other experiments have shown that horizontal web reinforcement has no impact, whereas the shear strength significantly increased as a function of vertical web reinforcement [4,5]. This contradiction in test results reflected on the design codes and standards. The methods in ACI 318-14 [6] and CSA A.23.3-14 [7] for estimating the shear strength of squat walls only consider the amount of horizontal reinforcement. Nevertheless, both codes recognize that vertical web reinforcement is essential to maintain the equilibrium of internal forces. On the other hand, the methods in Euro Code 8 [8] for estimating the shear strength of concrete squat walls consider both horizontal and vertical web reinforcement. All codes and standards cited above, however, require a minimum amount of horizontal and vertical web reinforcement be provided to control crack propagation and width.

In practice, squat walls are being used in low-rise structures such as parking garages and overpass bridges, which are exposed to severe environmental conditions in northern climates that cause the corrosion of steel reinforcement. The use of glass-fiber-reinforced-polymer

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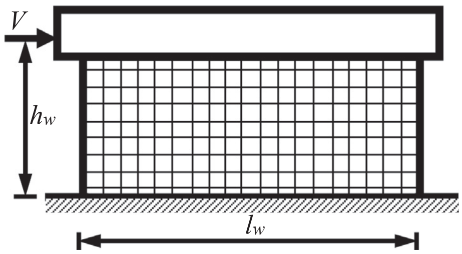

Fig. 1. Squat-wall geometry.

(GFRP) bars as a viable alternative reinforcing material has grown to obviate corrosion issues while providing an acceptable level of performance [9,10]. Mohamed et al. [11,12] investigated the applicability of using GFRP as internal reinforcement for earthquake-resistant systems such as mid-rise shear walls. The test results demonstrated the potential of GFRP reinforcement for distributing shear deformations along the wall height, owing to its elastic behavior, resulting in controlled shear distortion relative to the steel-reinforced wall. This result motivated a new study to evaluate the feasibility of using GFRP bars in squat walls, in which these problems are dominant. Arafa et al. [13] reported the testing of five squat walls with a shear span-to-length ratio of 1.7: one was reinforced with steel bars, the others with GFRP bars. The objective of the research study reported by Arafa et al. [13] was to investigate the applicability of reinforcing squat walls with GFRP bars. The test results clearly showed the stable behavior of the GFRP-reinforced squat wall through its hysteretic response, since it evidenced no load degradation or signs of premature shear failure compared to the steel-reinforced one. The results also demonstrated that the attained drift ratio satisfied the limitation in most building codes. Nevertheless, FRP has not been adopted yet by the relevant design codes and guidelines [9,10] as internal reinforcement for squat walls under seismic loads.

This paper aimed at experimentally assessing the impact of web reinforcement on the response of concrete squat walls totally reinforced with GFRP bars under quasi-static reversed cyclic loading. The experimental results were analyzed considering the crack pattern, mode of failure, drift capacity, ultimate load capacity, and load-displacement hysteretic response. The distribution of strains in either the vertical or horizontal direction is documented. The effect of horizontal and vertical web reinforcement on the concrete shear resistance is discussed.

2. Experimental program

2.1. Description of test specimens

A total of six full-scale rectangular concrete squat walls entirely reinforced with GFRP bars were constructed and tested. The tested specimens are half the size of typical squat walls used in the field. Two of the tested walls were reported on in Arafa et al. [13] to assess the failure progression, drift capacity, ultimate load capacity, energy dissipation, and prediction of ultimate strength of the GFRP-reinforced squat walls. The other four specimens are newly reported on in the current study to investigate the effect of the web reinforcement on the hysteretic response of GFRP-reinforced squat walls. Each test specimen measured 200 mm thick, 1500 mm long, and 2000 mm high. The wall thickness satisfied the CSA A23.3-14 [7] minimum thickness requirement in Clause 14.1.7.1. Each specimen was cast vertically to reproduce construction practice, with an integral 2700 × 1200 × 700 mm heavily reinforced foundation functioning as anchorage for the vertical reinforcement and to fasten the specimen to the laboratory floor. Fig. 3 provides the concrete dimensions and reinforcement details.

Two boundary elements of equal width and breadth (200 × 200 mm) were placed on each side of the squat walls (Fig. 3). The longitudinal and transverse reinforcement ratios at the boundary elements were kept constant in all specimens: 1.43% and 0.89%, respectively. The longitudinal reinforcement consisted of 8 No. 10 GFRP bars laterally tied against premature buckling with transverse reinforcement consisting of No. 10 spiral GFRP ties spaced at 80 mm along the wall height.

The main objectives of the experimental program were to investigate the effect of the horizontal and vertical web reinforcement. Four specimens—G4-250, G4-160, G4-80, and G6-80—were reinforced with different horizontal web reinforcement ratios; 0.51%, 0.79%, and 1.58%, and 3.58%, respectively, using No. 13 GFRP bars spaced at 250, 160, and 80 mm and No. 19 GFRP bars spaced at 80 mm, respectively. The vertical web reinforcement was kept constant and comprised of No. 10 GFRP bars spaced at 120 mm with a reinforcement ratio of 0.59%.

The two remaining specimens were constructed with either vertical or horizontal web reinforcement (G-V and G-H, respectively) to assess the effect of the absence of horizontal or vertical web reinforcement on wall behavior. Wall G-V was reinforced with vertical web reinforcement identical to that used in the four specimens, while wall G-H was reinforced with horizontal web reinforcement identical to that used in wall G4-250. The sliding shear was prevented by adding two layers of bidiagonal No. 10 GFRP bars across the potential sliding plane at an angle of 45° spaced at 100 mm. The detailed calculation of sliding shear can be found in Arafa et al. [13]. All reinforcement crossing the wall–base joint was anchored to the base with a development length in compliance with the requirements of CSA S806-12 [10] multiplied by a factor of 1.25 to account for the effect of compression and tension cycles as suggested by Mohamed et al. [11]. Table 1 gives the test matrix and reinforcement details.

2.2. Material properties

The test specimens were made with normal-weight, ready-mixed concrete with a target 28-day compressive strength of 40 MPa. Table 1 provides the actual concrete compressive strength (f_c') based on the average of at least three 100 × 200 mm cylinders for each concrete batch tested on the day of wall testing.

The longitudinal GFRP reinforcing bars were V-ROD™ sand-coated bars manufactured by a Canadian company (Pultrall Inc. [14]): No. 10 was used for longitudinal bars, either in the boundary element or in the web (Fig. 3) (f_{fu} = 1372 MPa, E_f = 65 GPa, ε_{fu} = 2.1%, A_f = 71 mm^2) and spiral ties (for straight portions: f_{fu} = 1065 MPa, E_f = 50 GPa, ε_{fu} = 2.1%, A_f = 71 mm^2; for bent portions: f_{fu} = 460 MPa). Two diameters were used as horizontal web reinforcement: No. 13 (for straight portions: f_{fu} = 1020 MPa, E_f = 50 GPa, ε_{fu} = 2%, A_f = 127 mm^2; for bent portions: f_{fu} = 459 MPa), and No. 19 (for straight portions: f_{fu} = 1028 MPa, E_f = 50 GPa, ε_{fu} = 2%, A_f = 285 mm^2; for bent portions: f_{fu} = 463 MPa). The horizontal reinforcement in the walls had 90° end hooks. Fig. 4 shows the GFRP bars and tie spirals used. The tensile properties of the straight GFRP bars were specified based on testing five specimens according to ASTM D7205/D7205M-06 [15]. The B.5 test method stipulated in ACI 440.3R-04 [16] was used to determine the tensile properties of the bent bars. The B.5 test method evaluates the bend strength of a FRP stirrup by embedding it in two concrete blocks, which are pushed apart until the FRP bent bar ruptures. A detailed description of the B.5 test method can be found in Ahmed et al. [17]. The reported tensile properties of the GFRP bars were calculated using the bar nominal cross-sectional areas.

2.3. Test setup and procedure

Fig. 5 shows the layout of the test setup. All specimens were tested laterally as a vertical cantilever with a force applied through a rigid steel loading beam, designed to transfer lateral loads across the top of the wall. The lateral cyclic loading was applied at 2550 mm above the base of the wall using a 1000 kN MTS hydraulic actuator with a maximum stroke of ± 250 mm. The base of each specimen was attached to the strong laboratory foundations through four prestressing high-