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Numerical simulation of mid-rise concrete shear walls reinforced with GFRP bars subjected to lateral displacement reversals

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ABSTRACT

This study represents a new step in using the finite-element method (FEM) as a powerful tool to simulate the seismic behavior of shear walls reinforced with glass-fiber-reinforced polymer (GFRP) reinforcement, which were tested and demonstrated the method's applicability as a lateral resisting system. The simulation analysis was performed on four large-scale mid-rise reinforced-concrete shear walls—one reinforced with steel bars and three totally reinforced with GFRP bars. Plane-sectional analysis and FE simulation were conducted, capturing the main features of this behavior. The results showed the stability and compliance of the simulation procedures used and provided reasonably accurate simulations of strength and deformation capacity. Shear distortion was evaluated and proved the effectiveness of the elastic behavior of the GFRP bars in controlling and reducing shear effect. These promising results can provide impetus for constructing shear walls reinforced with GFRP bars and constitute a step toward proposing design models for such new lateral-resisting systems.

1. Introduction

The use of fiber-reinforced-polymer (FRP) composite materials has been growing in an effort to overcome the infrastructure deterioration owing to the corrosion of steel reinforcement. One type of public infrastructure facing corrosion problems is the multistory parking garage, classified as a mid-rise building. Therefore, constructing a structural member with adequate stiffness and deformation capacity to resist lateral loads induced by wind or earthquakes is essential to building a parking garage with adequate corrosion resistance.

A previous study performed by Mohamed et al. [1] indicated that well-designed shear walls reinforced with glass-fiber-reinforced-polymer (GFRP) reinforcement can provide excellent lateral resistance while experiencing no strength degradation and demonstrating acceptable deformation capacity and energy dissipation in comparison to steel-reinforced shear walls. These results point to the need for more research on GFRP-reinforced shear walls. In addition to experimental studies, the finite-element method (FEM) can be a powerful tool in simulating shear-wall behavior and yield more comprehensive results for use in establishing an accurate design model for such shear walls.

Palermo and Vecchio [2] reported that the ability to predict the peak strength of steel-reinforced shear walls under seismic excitations was not well established. The predictions were based on the FEM, static monotonic and static cyclic analyses, FEM dynamic analyses, simplified static and dynamic analyses, and lumped-mass dynamic analyses. The results indicated that the methods and models used could predict the maximum load more accurately than the displacement at maximum load [3].

These apparent difficulties with accurately modeling ductility led to full-scale testing of FRP-reinforced shear walls at the University of Sherbrooke. The purpose of this experimental program was to investigate the behavior of shear walls reinforced with FRP bars under cyclic loading, to provide test data to formulate improved cyclic models, and to assess current capabilities in predicting structure ductility using FEM programs. Therefore, one of the main objectives of this paper is to briefly discuss the results of the experimental program and predict the shear-wall response based on plane sectional analysis and FEM simulation. Analyses using provisional constitutive models are presented to show that computational procedures can be stable and compliant, and can provide reasonably accurate simulations of behavior.

Assessing the flexural and shear strength of a wall panel was also addressed. This is especially important for earthquake-resistant

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design, in which the design load increases as the structure's ductility or deformation capability decreases. Even though this consideration is implicitly incorporated into building codes and may not be of direct concern to the designer, such information is important for developing or improving code provisions as well as for assessing the seismic safety of a particular design.

2. Summary of the experimental program and results

The experimental program comprised the testing to failure of four full-scale reinforced-concrete shear walls, including one reference steel-reinforced specimen (ST15) and three GFRP-reinforced specimens (G15, G12, and G10) under quasi-static loading. The specimens represent a model of a single mid-rise shear wall. Fig. 1a shows the concrete dimensions of the shear-wall specimens. ST15 served as a reference for G15, since it had the same concrete dimensions and similar reinforcement axial stiffness (140 and 124.2 MN for ST15 and G15, respectively). Wall specimens were designed with an adequate amount of distributed and concentrated reinforcement to ensure flexural domination and to prevent shear, sliding shear, and anchorage failures according to CSA A23.3-04 [4] and ACI 318-08 [5] for the steel-reinforced wall, whereas CSA S806-12 [6] and ACI 440.1R-06 [7] were used for the GFRP-reinforced walls, where applicable. Fig. 1b and Table 1 show the typical reinforcement details of the GFRP-reinforced shear walls.

One 1000 kN capacity servo-controlled MTS actuator and two hydraulic jacks (1000 kN capacity each) were used to apply the loads. The two hydraulic jacks were positioned vertically on the top of the steel loading beam to apply constant axial compressive loading during testing. The reaction of the hydraulic jacks was transferred through Dywidag bars to the wall's rigid base that had been fastened to the laboratory's strong floor. The actuator was positioned horizontally between the steel loading beam and the lateral reaction wall. Out-of-plane bracing was provided to prevent out-of-plane movement during testing. Fig. 1c shows the details of the test setup. A series of linear variable-differential transducers (LVDTs) and strain gauges were used to measure critical-response quantities, as shown in Fig. 1d.

The axial load was applied first and maintained at a constant level ($0.07 b_w \cdot l_w \cdot f_c'$) throughout the test. The horizontal load was applied in displacement control mode with a stroke of 1.2 mm/min. Lateral displacement reversal was applied starting with two cycles at 2 mm lateral displacement, then two cycles at each displacement level in increments of 2 mm up to a lateral displacement level of 10 mm, then increments of 5 mm up to 50 mm lateral displacement, and then increments of 10 mm up to failure. Table 2 lists the mechanical properties of the reinforcing bars. Fig. 2 shows the actual stress–strain curves for the concrete and the straight and bent GFRP bars.

Table 1
Wall reinforcement details.

Wall	f'_c (MPa)	Reinforcement ratio			
		ρ_v	ρ_h	ρ_l	ρ_t
ST15	39.2	0.23	0.63	0.50	0.63
G15	39.9	0.58	1.58	1.43	0.89
G12	39.8	0.62			
G10	40.2	0.59			

f'_c = concrete compressive strength.
ρ_v = web vertical-bar reinforcement ratio.
ρ_l = boundary longitudinal-bar reinforcement ratio.
ρ_h = web horizontal-bar reinforcement ratio.
ρ_t = boundary-tie reinforcement ratio.

Fig. 3 shows the envelope curves for the tested walls. In the early stages, ST15 achieved a higher load than G15, due to the softened response of G15 up to a lateral drift of 2.1%, corresponding to 99% and 80% of ultimate load for ST15 and G15, respectively. After that point, G15 kept increasing almost linearly to failure. Failure was due to concrete crushing following buckling of the longitudinal steel bars in ST15 and was associated with longitudinal and transverse rupture of the GFRP bars in G15, G12, and G10. The concrete cover of ST15 and G15 split, which is considered moderate damage, at similar loads but at different drift levels of 1.43% and 2% for ST15 and G15, respectively. The drift value reached for moderate damage to the GFRP-reinforced wall falls within the range of 1.5–2.5%, which is the recommended design range for drift found in many codes [8]. This is not a major concern for moderately ductile and ductile steel-reinforced walls, as more ductility is expected to increase the deformation capacity. Detailed discussion for specimens, testing procedure, and experimental results can be found in Mohamed et al. [1].

3. Prediction of ultimate load capacity

3.1. Plane sectional analysis

Plane sectional analysis was carried out to predict the ultimate lateral load (V_f) of the tested mid-rise walls as the failure was predominantly flexural, considering the unconfined and confined

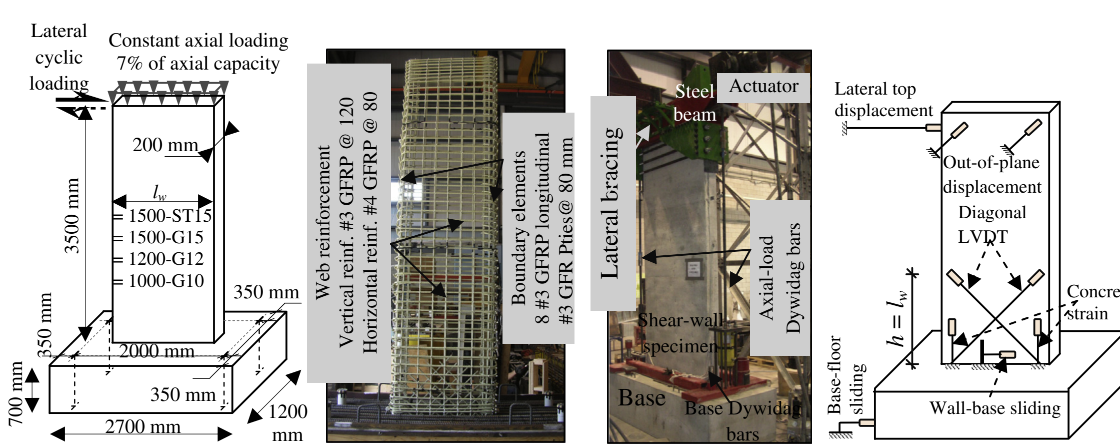

Fig. 1. Concrete dimensions, reinforcement details, test setup, and instrumentation.