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Analytical model for hybrid FRP-steel reinforced shear walls

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ABSTRACT

Experimental studies showed that concrete shear walls reinforced exclusively with GFRP bars had satisfactory strength and stable cyclic behavior, making them suitable for use in areas with low seismic risk. However, in areas in which the lateral demands are higher, the GFRP reinforcement might be inadequate due to the brittle nature of the material, and its reduced energy dissipation capacity. In this study, a finite-element (FE) analysis model for hybrid GFRP-steel reinforced shear walls for moderate seismic demands was developed. The steel lent ductility to the system, while the GFRP material enhanced the self-centering ability of the wall to reduce permanent displacements. The analysis model was first validated with experimental results obtained from steel- and FRP-reinforced walls from literature, and then used to determine the most suitable hybrid scheme combining ease of construction, maximum ductility, and minimum residual displacements. It was shown that hybrid walls have comparable strength and ductility to conventional steel-reinforced shear walls, while having better self-centering capacity under lateral loads. Simplified nonlinear dynamic analyses were conducted to study the performance of hybrid systems subjected to four earthquakes. The response of RC and hybrid steel-FRP walls were shown to be comparable when designed properly in terms of stiffness and serviceability.

1. Introduction

Fiber-reinforced polymer (FRP) bars are a feasible alternative to steel in reinforced concrete (RC) structures in areas where environmental conditions are adverse to steel reinforcement, since FRP-reinforced elements can be designed to have comparable ultimate strength and serviceability performance as conventional steel-reinforced members [1]. Under cyclic loading, the load-displacement response backbone of FRP-reinforced members is approximately bilinear, with reduced energy dissipation and residual displacements in each cycle [2,3]. Smaller permanent displacements are desirable with the potential of reducing repair and rehabilitation costs after a seismic event. While research on concrete members reinforced with FRP bars has focused on beams, columns and slabs [4–8], studies on FRP-reinforced shear walls are scarce [9]. Mohamed et al. [2,9] tested three shear walls completely reinforced with glass FRP (GFRP) bars under cyclic loading up to drift ratios of 3%. The walls had three different aspect ratios. Although the energy dissipation capacity of the walls was low when compared to a companion steel-reinforced wall, it was found the GFRP walls exhibited satisfactory strength and resilience, with no strength degradation up to failure. These features would make GFRP walls suitable for use in areas with low seismicity, in which minimization of permanent displacements allows for affordable repairs and immediate occupancy after the event [10]. Evidently, in areas in which the lateral demands are greater, this solution might be inadequate since the typical hysteretic response of a FRP-reinforced structure exhibits little ductility and limited energy dissipation. Therefore, as an alternative, the use of hybrid reinforcement consisting of steel and FRP rebars is proposed in shear walls. Steel lends ductility and energy dissipation to the wall, while the FRP material provides self-centering capacity. This idea has been implemented in columns in recent years. Wu et al. [11] proposed a novel composite bar made with FRP skin over a steel core to improve the post-yield stiffness of concrete columns. Fahmy et al. [12] and Sun et al. [13,14] investigated seismic behavior of columns reinforced with these composite bars experimentally and numerically. Cai et al. [15] tested four full-scale columns reinforced simultaneously with both carbon FRP (CFRP) bars and conventional steel bars. While these studies showed the potential of hybrid reinforcement to reduce residual displacements and improve post-yield stiffness of columns, no studies has been conducted on hybrid FRP-steel reinforced shear walls yet.

Since experimental data on this type of hybrid walls are unavailable, a robust analysis model verified with results obtained from FRP-reinforced and steel-reinforced concrete walls, would be a useful tool to understand the behavior of the hybrid system, and make valuable design recommendations. In this study, such an analysis model for low-

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rise shear walls was developed using the finite-element (FE) method. First, an FE analysis model for walls reinforced entirely with either FRP or steel bars was developed and validated with experimental results from the literature. Next, the model was used to investigate important aspects of design and response in several hybrid FRP-steel shear walls under in-plane loading. These aspects included placement of bars, strength, energy dissipation, and self-centering behavior. Both non-linear static and dynamic analyses were used to study the walls. The advantages and limitations of the proposed hybrid FRP-steel reinforcing system were discussed.

2. Analysis model for FRP- and steel-reinforced shear walls

Finite-element program Vector2 [16] was used to develop the analysis models for FRP- and FRP-steel reinforced shear walls. Developed for analysis of reinforced-concrete structures, program Vector2 is based on the Modified Compression-Field Theory (MCFT), in which concrete is modeled as an orthotropic material with smeared, rotating cracks. The ability of program Vector2 to predict the response of steel-reinforced shear walls has been shown in numerous research studies [17–23].

In the analysis model prepared in this study, the pre-peak and post-peak behavior of the concrete in compression were modeled using Popovics high-strength model [24] for concrete and the modified Park-Kent model [25], respectively. The Palermo model [26] was selected for the hysteretic response of the concrete to account for stiffness and strength degradation of the reloading branches. The strength of confined concrete was calculated using Kupfer-Richart model [27]. Default parameters for compression softening, dilation and cracking in the concrete were used as suggested by Palermo and Vecchio [19]. Detailed information of mentioned models for concrete were available in the software manual [16]. The steel was defined using a tri-linear relationship. The hysteretic response of steel reinforcement was modeled using Seckin model [28]. GFRP and CFRP were modeled as a brittle perfectly-elastic material. The non-linear tension softening base curve proposed by Yamamoto [29] and the Kharal-Sheikh model for tension stiffening [30] developed recently for steel- and GFRP-reinforced concrete, were used in the analysis model. The shear reinforcement (stirrups) were modeled as uniformly-distributed (smeared) reinforcement. This approach allowed for a simpler and faster analysis compared to the alternative of using discrete truss elements for reinforcing bars, while maintaining sufficient accuracy [22]. The vertical reinforcement were modeled as truss elements. Perfect bond between the reinforcement and concrete was assumed in the model as suggested in the literature for low-rise shear walls [19,20,22]. Four-node quadrilateral elements was used to model the concrete.

First, the model was validated against the three GFRP-reinforced walls tested by Mohamed et al. under cyclic loading and axial load (Fig. 1) [2,9]. These GFRP walls were all 3.5 m high, with a thickness of 0.2 m and widths of 1.5 m (specimen G15), 1.2 m (G12) and 1.0 m (G10). The mesh size was selected based on a sensitivity analysis, with smaller-sized elements at the bottom part to capture the higher non-linear behavior at the base of the cantilever walls (Fig. 2).

As reported by Mohamed [9], the concrete had a compressive strength of $f'_c = 40$ MPa on the test day. The sanded GFRP bars had an ultimate strength of 1412 MPa and a Young's modulus of 66,900 MPa. Fig. 2 shows the model developed for wall G12. Due to space considerations, results for walls G10 and G15 were not presented, but they were found to be similar. It was observed that the developed model was able to predict the stiffness, strength and failure of the walls with reasonable accuracy. The error in prediction of the strength and displacement capacity of three walls was less than 17%. The GFRP-reinforced specimens exhibited negligible residual displacements up to 80% of displacement capacity [9], which was in agreement with modeling results.

Since the model was used to study low-rise walls in this research, ability of the model to predict the response of two low-rise steel-reinforced specimen was checked next. The majority of available models were not able to predict low-rise walls response with reasonable accuracy due to considerable shear deformation of the walls [31]. For this purpose, the specimen M4 tested by Greifenhagen and Lestuzzi [32] was analyzed with the described model first. This specimen had aspect ratio of 0.69 as shown in Fig. 3. This lightly-reinforced wall was tested under axial load and static cyclic loading. The specimen exhibited flexural concrete crushing failure. The analysis results presented in Fig. 3 shows that the model predicted displacement capacity, strength, and residual displacements with less than 10% error. The second wall was CW-2 specimen with the detailing shown in Fig. 4 (aspect ratio of 1.2) tested by Lombard [33] under no axial load. The model was able to predict the residual displacements with a good accuracy (less than 10% error) (Fig. 4), while the strength was underestimated by 12%. Ability of VecTor2 to predict shear deformation of steel-reinforced low-rise walls was demonstrated in the literature as well [19,20].

Next, the model was used to predict the response of two of hybrid CFRP-steel reinforced columns (specimens S1F1 and S1F2) tested by Cai et al. recently [15]. These columns, which were tested under constant axial load and cyclic lateral displacements, exhibited rupture of CFRP bars. In the modeling, elastic behavior with Young's modulus 134 GPa and ultimate strength of 1592.4 MPa was assumed for the CFRP bars as reported by the authors [15]. Analysis results presented in Fig. 5 shows that model was able to predict the rupture displacement of CFRP bars with 9% difference and self-centering ratio of the hybrid member with 7% difference, while the ultimate displacement was overestimated by 6% due to considerable bond-slip between the concrete and CFRP bars in the experiment. Due to space considerations, results for S1F2 column was not presented, but it was found to be similar.

The failure modes predicted in these validation studies agreed well with the experimental observations. Both the damaged state and the change in stresses were readily identified in the graphics-based post-processor of VecTor2 (typically shown in Fig.6).

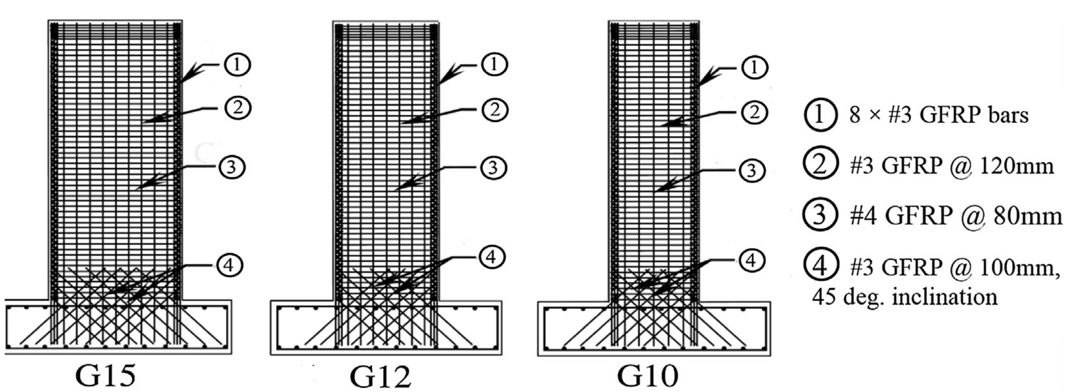

Fig. 1. GFRP-reinforced shear walls [2].