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Mechanisms of shear resistance of one-way concrete slabs reinforced with FRP bars

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HIGHLIGHTS

- We investigate the shear behavior of one-way FRP-reinforced concrete slabs.
- Shear behavior depends on the axial stiffness of FRP bars.
- We investigate the shear capacity of slabs using normal and high strength concretes.
- We assess the shear behavior in terms of crack patterns, and shear capacities.

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ABSTRACT

The shear behavior of concrete reinforced with fiber-reinforced polymer (FRP) but without web reinforcement is potentially the most critical case in shear-prone applications due to the brittle nature of the concrete and reinforcement and, as such, requires special attention. A total of 16 one-way reinforced concrete slabs reinforced with glass- and carbon-FRP bars in addition to steel-reinforcement were constructed and tested to failure under four-point flexural loading. Their structural behavior was observed and reported in terms of failure mechanisms, crack patterns, main shear cracks, and ultimate capacities. The test results confirmed the effect of the axial stiffness of longitudinal FRP reinforcement on shear strength. The use of high-strength concrete had a positive impact on the initial shear-cracking load and ultimate-load capacity. The influence of the reinforcement type, bar diameter, and bar shear stiffness on the mode of failure was determined and discussed. Most of the CFRP-reinforced slabs experienced brittle failure, while most of the GFRP reinforced slabs—with reinforcement axial stiffness equivalent to that of the CFRP reinforced slabs—kept their integrity even after failure, thereby avoiding brittle modes of failure.

1. Introduction

Fiber-reinforced-polymer (FRP) bars can be effectively used for construction applications to overcome corrosion problems. Reinforcement corrosion is especially an issue in structures—parking garages, bridge deck slabs, and the like—exposed to aggressive environments such as to deicing salts and freeze–thaw cycles. The advantages of FRP reinforcing materials include high strength-to-weight ratio, ease of handling and installation, and corrosion resistance [2,3,15]. Concrete members reinforced with FRP bars develop wider and deeper cracks than members reinforced with same amount of steel bars [13,14,22,17,29].

Compatibility of the reinforcement across a crack is achieved by a combination of stretching of the debonded reinforcement and slip of the bonded reinforcement relative to the concrete [27]. Sherwood et al. [25] showed that there is no discernible "width effect" in one-way shear failures and, therefore, beam test results are also applicable to slabs. Hoult et al. [18] concluded that there is no evidence that steel-reinforced and FRP-reinforced members without stirrups behave in a fundamentally different way. Predicting shear capacity is essential in designing FRP-reinforced concrete members because the design guidelines and codes [4,9] recommend over-reinforced designed sections, making them vulnerable to shear failure. Although large numbers of tests have been performed on FRP-reinforced elements, very limited research has investigated FRP-reinforced slabs [5,13,14,20,26].

Past shear provisions issued by the American Concrete Institute (ACI) that were unmodified to account for FRP-reinforced members

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yielded un-conservative results [30], so that new models were developed for FRP shear behavior. Indeed, a correlation was found between the reinforcement axial stiffness and shear capacity [28,13,14]. Some empirically calibrated equations can apparently work well for both steel- and FRP-reinforced members [29]. Bentz et al. [7] found that, despite the brittle nature of the FRP reinforcement, large concrete beams reinforced with FRP behaved similarly in shear to steel-reinforced concrete beams. Salib and Abdel-Sayed [23] suggested that future research could focus on assessing the influence of FRP-bar shear stiffness on concrete shear strength as well as on the contribution of FRP bars to the overall component shear capacity, particularly in shallow members with little or no shear reinforcement. According to Saiid [24], an increase in the concrete compressive strength of beams increases their ultimate shear strength. In spite of the available experimental studies performed on FRP-RC concrete, however, more experimental testing of slender members is still required to develop models that can accurately predict shear strength [11,6].

2. Objectives

This study investigates the shear strength of one-way concrete slabs reinforced with longitudinal FRP reinforcement subjected to flexural testing. Only members without transverse (shear) reinforcement were investigated. The amount of longitudinal FRP reinforcement and, more precisely, the axial stiffness of the longitudinal reinforcement, was considered the primary variable in a total of 16 one-way FRP-RC slabs. In this experimental program, various concrete compressive strengths were investigated as well as different types of FRP reinforcement. Direct comparison of the shear behavior, ultimate capacities, and cracking patterns is made. Differences in the shear behavior with various reinforcement types and concrete characteristics are explored, broadening our understanding of the fundamental shear behavior of one-way FRP-RC slabs.

3. Experimental program

3.1. Materials

Normal and high-strength concretes were used to fabricate the slab specimens with targeted compressive strengths of 45 MPa, 70 MPa, and 80 MPa. The compressive concrete strengths were determined by testing at least three 150 × 300 mm cylinders on the day of testing. The concrete compressive strengths for each slab are provided in Table 1.

Three types of GFRP bars were used in nine slabs. The GFRP bars had different moduli, according to Grade II and III [10], and surface textures (sand coated and helically wrapped). Only one type of CFRP bars was used in six slabs. Steel rebar was used in one slab serving as a control. The tensile properties of the FRP reinforcing bars were determined by testing five representative specimens according to ASTM D7205M [1]. The properties of the steel bars were provided by the manufacturer. Table 1 gives the mechanical properties of the reinforcing bars. More details on FRP bars testing can be found elsewhere [6].

3.2. Test specimens

Seventeen one-way slabs were cast for testing to failure under four-point flexural bending. The specimens had identical dimensions of 4000 mm in length, 1000 mm in width, and 200 mm in depth with a clear span of 3500 mm. All of the specimens had top and bottom reinforcement. All of the secondary and top reinforcement was #5 GFRP @ 300 mm. Fig. 1 depicts specimen geometry and reinforcement details; Table 1 gives the reinforcement configurations. The slabs were categorized into six groups according to the parameters studied. Similar axial stiffness of the main reinforcement was selected for each group (see Table 2 for the details for each group). The slabs were labeled according to the parameters studied. The first letter represents the bar type: G for glass and C for carbon; the second letter represents the FRP-bar surface texture and modulus of elasticity: D for standard modulus sand coated; H for high modulus sand coated; and W for helically wrapped and S for steel. The two numbers represent the number of bars and bar diameter, respectively.

Group A includes GW-56 and GD-46 reinforced with #6 GFRP helically wrapped and sand-coated bars, respectively. Both slabs had similar axial stiffnesses of 58,140 and 56,772 kN, respectively, to explore the effect that varying surface texture would have on shear behavior. In group B, the effect of concrete compressive strength on the behavior of high-modulus (HM) GFRP bars was investigated with three identically reinforced slabs with five #6 HM bars with an axial stiffness of 67,800 kN. The concrete compressive strengths for GH-56, GH-56$_A$, and GH-56$_B$ were 42.9, 77.4 and 82.6 MPa, respectively.

The three slabs in group C—CD-54, GD-58 and GH-56—were reinforced to have similar axial stiffnesses (102,854, 111,220, and 105,008 kN, respectively). This was to investigate what impact varying the reinforcement type would have on shear strength. Similarly, the effect of reinforcement type was investigated in Group D, but with a higher level of axial stiffness: the two specimens—CD-64 and GH-66—had similar axial stiffnesses of 123,426 and 126,010 kN, respectively.

Group E was formed to investigate the effect of concrete compressive strength on the behavior of CFRP-reinforced concrete slabs with three identically reinforced slabs. They were reinforced with five #4 bars with an axial stiffness of 139,200 kN. The concrete compressive strengths were varied in CD-74, CD-74$_A$, and CD-74$_B$: 52, 76, and 86.2 MPa.

The specimens in group F had the highest axial stiffnesses. The four slabs in this series were CD85 reinforced with 8 C15 bars, GH-66B reinforced with 12 G20 bars in bundle configuration, S-56

Table 1
Properties of the reinforcing bars.

Bar type[a]	D (mm)	A(mm)^2	f_t (MPa)	E_f (GPa)	ε_u (%)
CFRP	13	129	1906	147.7	1.20
	15	199	1680	141.0	1.20
Type I, Grade I GFRP	20	284	724	40.8	1.49
Type II, Grade I GFRP	20	284	666	49.8	1.50
	25	510	588	43.9	1.34
Type II, Grade III GFRP	20	284	1197	67.8	1.51
	25	510	1078	65.5	1.60
Steel	20 M	300	f_y = 460	E_s = 200.0	ε_y = 0.23

[a] According to CSA S807-10 (Grade I and Grade III GFRP bars) Type I helically wrapped bars, Type II sand-coated bars.