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SHEAR BEHAVIOR OF RC BEAMS STRENGTHENED WITH DIFFERENT TYPES OF FRCM: EFFECT OF STIRRUPS' CONFIGURATION

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Fabric-reinforced cementitious matrix, (FRCM) system has shown to be promising for the strengthening of reinforced concrete (RC) beams. However, the available experimental investigation on the shear strengthening efficacy of FRCM system is limited, particularly for deep beams. Moreover, to the authors' knowledge, no literature is available on the effect of the stirrups' configuration relative to the FRCM strips on the shear capacity of FRCM-strengthened beams. Studying this effect will aid in a better understanding of the FRCM/stirrups interaction. Thus, in this paper the experimental study on the shear behavior of RC deep beams strengthened in shear using FRCM system is presented. The test matrix involved two unstrengthened and six FRCM-strengthened deep beams tested under three-point bending. The primary test variable was the effect of stirrups' configuration relative to the FRCM strips. The other test variable includes the effect of different types of FRCM fabric (made of carbon, glass, and polyparaphenylene benzobisoxazole, PBO). Experimental results demonstrated an effective application of the FRCM in improving the load capacities of RC deep beams, up to 40.3% increase in the load capacity was achieved.

Keywords: Reinforced concrete, Deep beam, Strengthening, Fabric-reinforced cementitious matrix.

1 INTRODUCTION

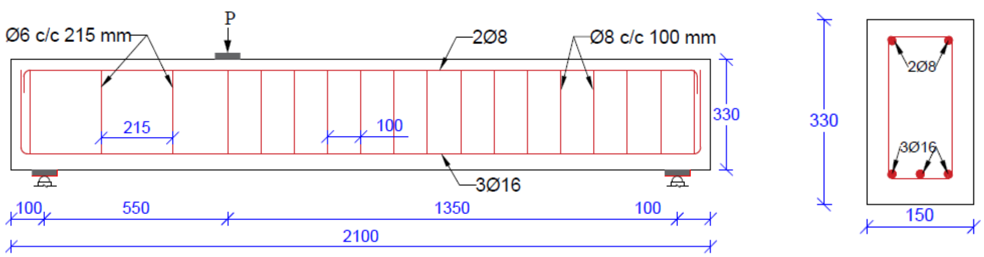
Fiber reinforced polymer (FRP) system has been widely implemented as an effective strengthening technique for reinforced concrete (RC) structures due to its light weight, ease of installation, an excellent resistance to corrosion, and high tensile strength (Aly *et al.* 2006, Ebead 2015, Ebead and Saeed 2013, 2014). However, some drawback associated with FRPs such as their incompatibility with the concrete substrate, low fire resistance, and high cost of resins limits their use. In order to overcome this problem, fabric reinforced cementitious matrix (FRCM) has been introduced by replacing the epoxy adhesives with cementitious mortar. FRCM system has successfully been used for the strengthening of RC beams both in shear (Ebead and Wakjira 2018a, Elghazy *et al.* 2018, Marcinczak and Trapko 2019, Ombres 2015, Wakjira and Ebead 2018c, 2019, Younis *et al.* 2017) and flexure (Ebead *et al.* 2017, Ebead *et al.* 2019, Ebead and El-sherif 2019, Elghazy *et al.* 2017, Pino *et al.* 2017) owning a better bond with the substrate concrete (Ebead and Younis 2019, Younis and Ebead 2018) relative to FRP. However, the available experimental investigation on the shear strengthening efficacy of FRCM system is limited. The shear strengthening efficacy of such system depends on various factors including but not limited to the application methods, wrapping schemes, and geometric configurations.

Moreover, previous experimental and analytical results has shown that the stirrups reinforcement ratio significantly affect the efficacy of the FRCM system (Awani *et al.* 2015, Ebead and Wakjira 2018b, Wakjira and Ebead 2018a, 2018b). Nonetheless, unlike FRP strengthening system, the study on the interaction of the FRCM/stirrups is scarce. Moreover, to the authors' knowledge, no literature is available on the effect of the stirrups' configuration relative to the FRCM strips on the shear capacity of the strengthened beams. Studying this effect will aid in a better understanding of the FRCM/stirrups interaction.

Thus, the present study investigates the structural performance of RC beams strengthened with an externally bonded FRCM. The strengthening was performed with three fabric plies embedded in the cementitious matrix. The effects of the stirrups' configuration (aligned and unaligned with the FRCM strips) and types of fabrics (carbon, glass, and polyparaphenylene benzobisoxazole (PBO)) were investigated.

2 EXPERIMENTAL PROGRAM

A total of eight medium-scaled RC beams, two unstrengthened/control beams and six strengthened beams, were used. Figure 1 shows the geometric and reinforcement details of the test beams. The specimens were internally reinforced with two 16 mm diameter tensile bars and two 8 mm diameter compressive bars with yield strengths of 595 MPa and 535 MPa, respectively. The shear reinforcement was done using 8 mm diameter bars spaced at 100 mm outside the shear span, while 6 mm diameter bars spaced at 215 mm were used within the shear span as shown in Figure 1. The yield strengths of the stirrups within and outside the shear span were 298 MPa and 234 MPa, respectively.



(a) Longitudinal detail (b) Cross-section

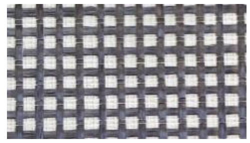
Figure 1. Geometric and reinforcement detail of the reference beam (all dimensions are in mm).

The beams were cast using normal weight ready-mix concrete with an average compressive strength of 30 MPa. Three different types of FRCM fabrics were used; viz., glass, carbon, and PBO fabrics as shown in Figures 2a through 2c along with their geometric and mechanical properties.

The strengthening is performed using 0.12 m wide FRCM strips spaced at 0.095 m as shown in Figures 3a and 3b. The test variables were the stirrups' configuration relative to the FRCM strips; namely, stirrups aligned versus unaligned with the FRCM strips as shown in Figures 3a and 3b, respectively, and the type of fabrics (glass, PBO, and carbon) as listed in Table 1. The test specimens are classified in to two groups based on the configuration of the stirrups relative to the FRCM strips. Group-1 beams are specimens internally reinforced with stirrups aligned with the FRCM strip, Figure 3a, while in Group-2 beams the stirrups are unaligned with the FRCM strips, Figure 3b.

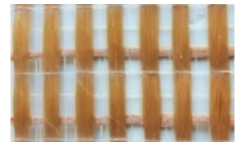
Grid spacing: 18.2 × 14.2 mm
Ultimate elongation: 0.0325
Elastic modulus (E_f): 80 GPa
Tensile strength: 2600 MPa
Area per unit width in the warp direction: 0.0477 mm

(a) Glass fabrics



Grid spacing: 10 × 10 mm
Ultimate elongation: 0.0180
Elastic modulus, E_f: 240 GPa
Tensile strength: 4800 MPa
Area per unit width in the warp direction: 0.0477 mm

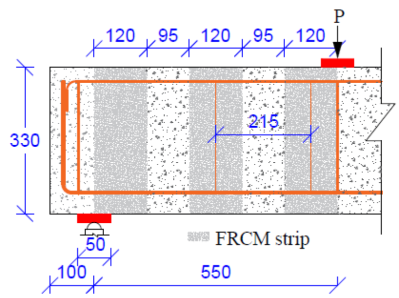
(b) Carbon fabrics



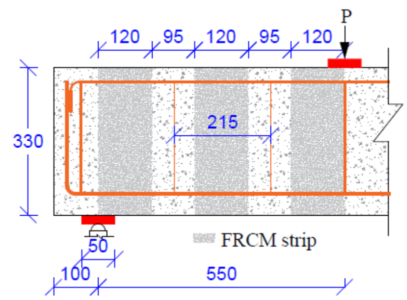
Grid spacing: 10 × 17 mm
Ultimate elongation: 0.0215
Elastic modulus, E_f: 270 GPa
Tensile strength: 5800 MPa
Area per unit width in the warp direction: 0.0455 mm

(c) PBO fabrics

Figure 2. Fabric types used in this study and fiber properties.



(a) Group-1



(b) Group-2

Figure 3. Strengthening configuration details (all dimensions are in mm).

3 TEST RESULTS AND DISCUSSION

The test results are summarized in Table 1 in terms of the ultimate load, P_u, and its corresponding deflection, δ_u, and the gain in P_u relative to the reference beams.

Table 1. Experimental test results.

Group	Beam ID[a]	FRCM fabric	P_u (kN)	Gain in P_u (%)	K_{ft} (kN)	δ_u (mm)
1[b]	B1	–	130	–	–	5.12
	BC1	Carbon	182	40.3	13705	7.54
	BG1	Glass	158	21.5	6091	6.36
	BP1	PBO	163	25.7	11007	7.52
2[c]	B2	–	138	–	–	6.02
	BC2	Carbon	188	36.6	13705	8.28
	BG2	Glass	161	16.6	6091	6.73
	BP2	PBO	175	26.8	11007	7.45

[a]B: beam, C: carbon, G: glass, P: PBO; [b]stirrups aligned with the FRCM strips;
[c]stirrups unaligned with the FRCM strips.

3.1 Ultimate Load and Failure Modes

The ultimate load (P_u) and the gain in P_u for FRCM-strengthened beams relative to the corresponding reference beam are listed in Column 4 and Column 5 of Table 1. The reference beam of Group-1 specimens, B1, failed at the ultimate load of 130 kN. The strengthened beams of the same group; namely, Specimens BC1, BG1, and BP1 failed at the respective ultimate loads of 182 kN, 158 kN, and 163 kN representing percentage gain in P_u of 40.3%, 21.5%, and 25.7% relative to B1 as listed in Table 1.

The strengthened specimens of Group-2; namely, BC2, BG2, and BP2 failed at the ultimate loads of 188 kN, 161 kN, and 175 kN, respectively. These load values represent 36.6%, 16.6%, and 26.8% increase in the ultimate load relative to B2 (138 kN) for Specimens BC2, BG2, and BP2, respectively as listed in Table 1.

For the FRCM type, carbon FRCM strengthened specimens showed higher gain in the load capacity relative to the glass and PBO counterparts regardless of the stirrups' configuration. This can be explained in terms of the FRCM axial rigidity (E_f), which is the product of the axial stiffness (E_f) and effective area (A_f) of the FRCM reinforcement as given in Table 1. For instance, Specimen BC1 from Group-1 with higher E_f value failed at the ultimate load of 182 kN representing 40.3% gain in the load capacity. The glass and PBO counterparts of the same specimen, BG1 and BP1, showed lower gain in P_u of 21.5% and 25.7%.

The effect of the stirrups' configuration on the percentage gain in the load capacity is illustrated in Figures 4a through 4c for glass, PBO, and carbon FRCM strengthened beams, respectively. As can be seen in these figures, generally, aligned FRCM/stirrups resulted in a slightly higher gain in the load capacity. However, this difference in the load capacity is not significant, less than 5%.

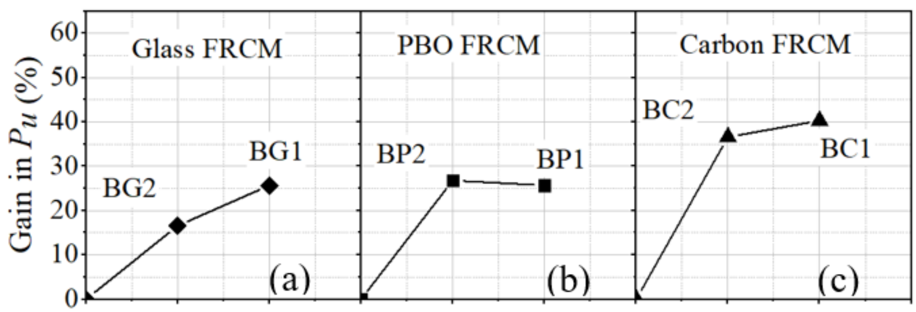


Figure 4. The effect of stirrups' configuration on the gain in the ultimate load.

All tested beams failed in shear with the formation of a diagonal shear crack. The strengthened beams failed in shear with a premature delamination of the FRCM laminate off the concrete substrate as shown in Figures 5a and 5b for Specimens BC1 and BP1, respectively. This is a typical mode of failure of specimens strengthened with an externally bonded FRCM system.

(a) BC1 (b) BP1

Figure 5. Typical failure modes of the strengthened beams.

3.2 Deformational Characteristics

Figures 6a and 6b show the load–deflection responses of the tested beams, while the ultimate deflection (δ_u), i.e., the deflection at the ultimate load is given in Table 1. In general, all the tested beams showed a bilinear load–deflection response with a partial linear curve before and after failure. The strengthened beams experienced higher deflection at the ultimate load relative to the unstrengthened beams as shown in Figures 6a and 6b. The maximum deflection of up to 8.28 mm, was observed for the strengthened specimens as can be seen in Figure 6 and Table 1. This observation indicates the efficacy of the FRCM system in enhancing the load–deflection response of the strengthened beams.

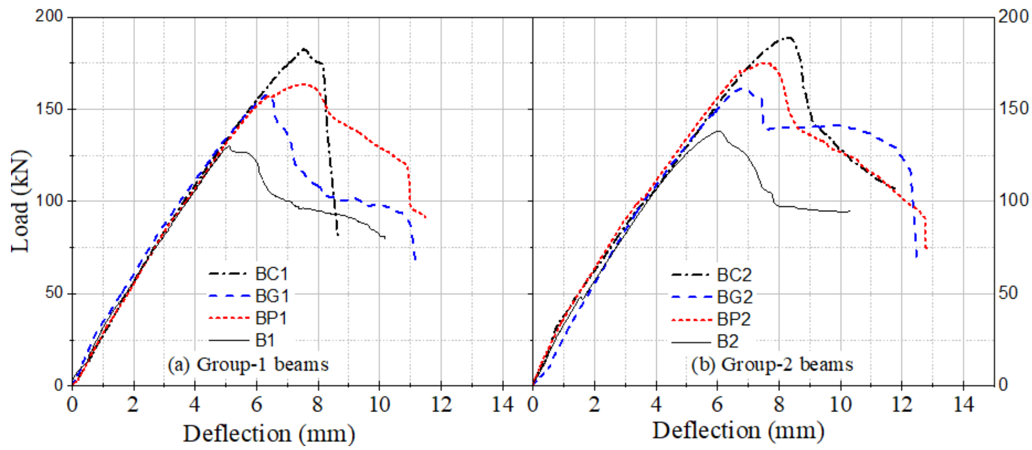


Figure 6. Load–deflection diagram.

4 CONCLUSIONS

In this paper, an experimental study on the shear behavior of fabric-reinforced cementitious matrix, FRCM-strengthened reinforced concrete (RC) beam was presented. Different types of commercially available FRCM fabrics were used along with their associated manufacturer recommended mortars including glass, carbon, and polyparaphenylene benzobisoxazole fabrics. The effect of stirrups' configuration relative to the FRCM strips and the type of the FRCM fabrics on the load capacity, failure modes and deformational characteristics of the strengthened beams were studied. All beams failed in shear with a formation of main diagonal shear crack running from the loading point to the support. The following conclusions can be drawn from this study:

Regardless of the stirrups' configuration, the FRCM system has considerably increased the load capacities of the strengthened beams. The gain in the ultimate load ranged from 16.6% to 40.3% relative to the reference beams and this enhancement depends on the tested variables.

The stirrups' configuration relative to the FRCM strips does not show a significant effect on the percentage gain in the load capacities of the strengthened beams. A maximum of 4.9% gain in the ultimate load was observed by aligning the stirrups with the FRCM strips compared to the unaligned FRCM/stirrups configuration.

The specimens strengthened with carbon FRCM showed a higher gain in the load capacity than the PBO and glass FRCM counterparts due to its the higher axial rigidity compared to the others.

Acknowledgments

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