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BOND AND SHEAR-STRENGTHENING PERFORMANCE OF FRCM COMPOSITES

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This paper is aimed at studying the bond and shear-strengthening performance of fabric reinforced cementitious matrix (FRCM) systems. Three FRCM systems were compared, namely, polyparaphenylene benzobisoxazole (PBO)-FRCM, Carbon-FRCM, and Glass-FRCM. At first, six double-shear specimens were tested to investigate the FRCM/concrete bond, with the test variables including the fabric type and the bond length. After that, seven shear-critical reinforced concrete (RC) beams were tested under three-point loading, considering the fabric type and strengthening configuration (full/intermittent) as the test variables. As for the double-shear test results, the failure observed was fabric/matrix debonding in carbon-FRCM, matrix/concrete debonding in PBO-FRCM, and fabric rapture in glass-FRCM. The FRCM/concrete bond increased with the bonded length, and the PBO-FRCM showed the highest bond to concrete. Regarding the RC beam tests, the FRCM-strengthened beams showed the same failure mode that is debonding at the FRCM/concrete interface. Nonetheless, FRCM had successfully strengthened the beams in shear: an average gain of 57% in the load carrying capacity was achieved as compared to the non-strengthened reference. Indeed, the full-length strengthening resulted in a better structural improvement compared to the intermittent-strengthening configuration. Amongst the three systems, carbon-FRCM systems were the most efficient in shear-strengthening RC beams.

Keywords: Textile-reinforced mortar, Fabric-reinforced cementitious matrix, Bond capacity, Debonding, Rehabilitation.

1 INTRODUCTION

Deterioration of reinforced concrete (RC) structures is inevitable due to the various load and/or environmental exposures encountered during their life cycle (Younis *et al.* 2018), therefore, different strengthening techniques were proposed as a remedial measure such as ferrocement (Ebead 2015) and fiber reinforced polymer (FRP) (Ebead 2011, Ebead and Saeed 2014). Recently, fabric reinforced cementitious matrix (FRCM) has emerged as a viable solution for RC strengthening. FRCM includes dry fibers impregnated in a cementitious matrix, and is surface-applied for strengthening RC and masonry structures (Akbari Hadad *et al.* 2018, Ebead *et al.* 2017, Pino *et al.* 2016, Younis *et al.* 2017a). FRCM was demonstrated as an efficient technique for shear strengthening RC beams (Wakjira and Ebead 2018a, Wakjira and Ebead 2018b, Younis *et al.* 2017b, Younis *et al.* 2017c). Nonetheless, it is agreed that a sufficient understanding of the FRCM/concrete bond is essential to maximize its potential use in RC strengthening: some research efforts have been dedicated in the past few years for such purpose (Raoof *et al.* 2016, Shrestha *et al.* 2017, Younis and Ebead 2018). Given that, the current paper has a two-fold objective: (a) to investigate the bond between different FRCM systems and concrete; (b) to investigate the effectiveness of FRCM systems in shear-strengthening RC beams, with more focus on the failure behavior.

2 EXPERIMENTAL PROGRAM

2.1 Materials

Ready-mixed concrete with a 28-day compression strength of 30 MPa was used to cast the RC beams and the double-shear specimens. Grade 500B (ISE/104 Committee 2005) steel bars were used to reinforce the concrete beams. The yield stress, yield strain, and modulus of elasticity of the reinforcing bars were measured as 595 MPa, 0.266%, and 224 GPa, respectively. Three FRCM systems were adopted, namely, carbon-FRCM (Ruredil 2016a), polyparaphenylene benzobisoxazole (PBO)-FRCM (Ruredil 2016b), and glass-FRCM (SIKA 2016). The FRCM system typically included a single layer of fabric impregnated between an internal (attached to concrete) and external mortar layers. Table 1 lists the mechanical properties of each fabric provided by the manufacturer.

Table 1. Properties of fabric (warp direction) for the FRCM systems.

Fabric type	Area per unit width (mm^2/mm)	Elastic modulus (GPa)	Tensile Strength (GPa)	Ultimate strain (%)
PBO	0.045	270	5.80	2.15
Carbon	0.047	240	4.8	1.8
Glass	0.047	80	2.6	3.25

2.2 Test Specimens

For the double-shear test, six 150-mm concrete cubes were prepared: for each, FRCM system was applied to create a double-shear connection (Figure 1-a). A uniform bond width of 100 mm was considered. Two test parameters were investigated as shown in Table 2: (i) fabric type (glass/carbon/PBO); and (ii) bond length (75 or 100 mm).

For the beam test, seven shear-critical RC beams (of 2,500 mm in length, 150 mm in width, and 330 mm in depth as shown in Figure 1-b) were cast, of which one was kept non-strengthened and used as a reference. The rest of the beam specimens were strengthened considering two test variables as shown in Table 3, namely, (i) fabric type (carbon/PBO/glass); and (ii) strengthening configuration: a single full-length FRCM plate or a set of three intermittent 120-mm wide FRCM strips were applied along the critical shear zone.

2.3 Test Setup

For the double-shear test, FRCM was axially loaded by stretching the fabric from the specimen's opposite sides using a hydraulic jack operated at an approximate rate of 4 mm/min (Figure 1-a). A curved-edge steel plate was placed between the hydraulic jack and the stretched fabric so that the load was uniformly distributed within the fabric mesh and, hence, stress concentrations were mitigated. A cylindrical load cell of 500-kN capacity was placed between the hydraulic jack and the test specimen to monitor the load applied. The FRCM slip was measured using a linear variable displacement transducer (LVDT).

The RC beams were tested under three-point loading: each beam was subjected to a displacement-controlled loading at a rate of 1 mm/min. Vertical displacement was measured by an LVDT at the location of the loading point (Figure 1-b). Data acquisition of the measurements was performed at a frequency of 1 Hz.

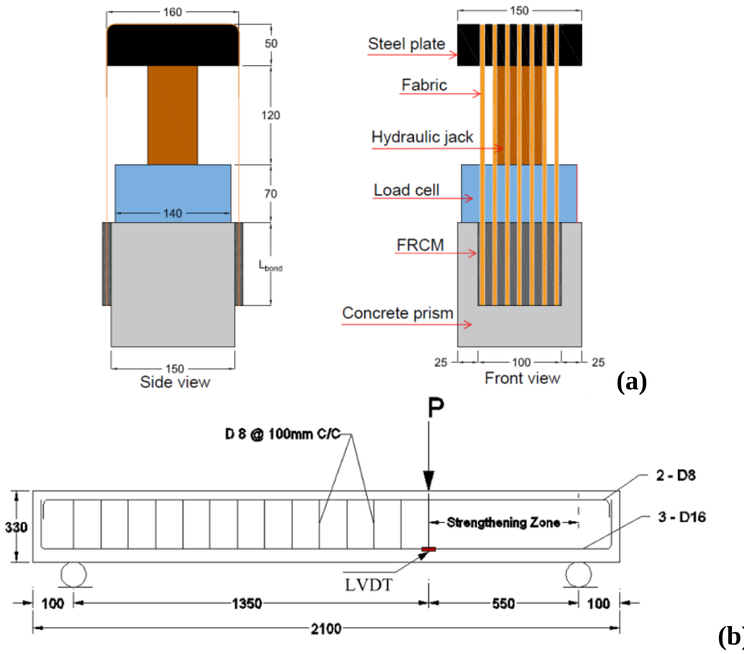

Figure 1. Details for (a) double-shear test specimen, and (b) RC beam specimen.

3 RESULTS AND DISCUSSION

3.1 Bond Performance

Table 2 presents a summary of the double-shear test results. The ultimate shear stress (τ_u) was calculated as the failure load (P_u) divided by the total FRCM bonded area. The average shear-stress capacity of the FRCM/concrete bond was 530, 273, and 265 kPa for PBO-, carbon-, and glass-FRCM systems, respectively; thus, the PBO-FRCM had the highest bond to concrete. As intuitively expected, the FRCM/concrete bond increased with the bond length: the average improvement in the FRCM/concrete bond as a result of increasing the bond length (from 75 to 100 mm) was 94, 37, and 81% for carbon-, PBO-, and glass-FRCM systems, respectively.

Table 2. Summary of the bond test results.

Specimen	Fabric type	Bond length (mm)	P_u (kN)	τ_u (kPa)	δ_u (mm)	Failure mode*
C-L75	Carbon	75	3.34	222	4.2	FD
C-L100	Carbon	100	6.48	324	5.5	FD
P-L75	PBO	75	7.85	523	≈ zero	DB
P-L100	PBO	100	10.75	538	0.03	DB
G-L75	Glass	75	3.38	225	0.03	FR
G-L100	Glass	100	6.11	305	0.09	FR

*FD: Fabric/matrix debonding; DB: Debonding at the concrete/matrix interface; FR: Fabric rapture.

Regarding the failure modes, the carbon-FRCM system showed debonding at the fabric/matrix interface (FD) (Figure 2-a). The PBO-FRCM system exhibited debonding at the concrete/matrix interface (DB) (Figure 2-b). The failure mode for the glass-FRCM system, however, was a premature rupture of the stretched fabric (FR) (Figure 2-c) – mostly attributed to the relatively lower tensile strength of the glass fibers (Table 1). Thus, the bond failure was more brittle in glass- and PBO-FRCM systems; this can be further evidenced by their lower FRCM slip at failure (δ_u) as compared to that of carbon-FRCM (Table 2).

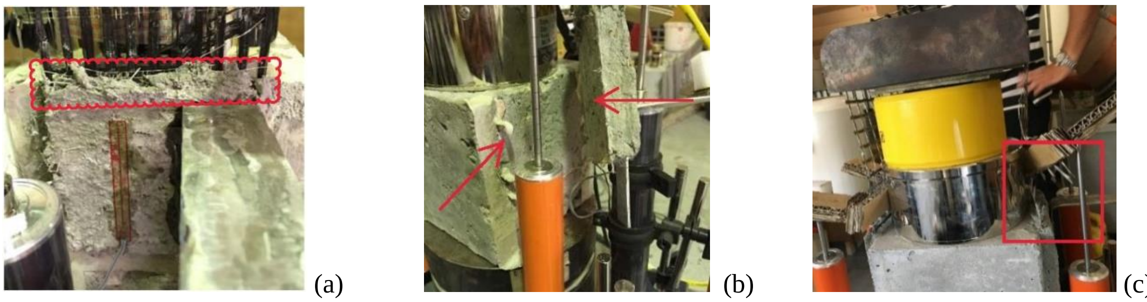

Figure 2. Failure modes – (a) FD in carbon-FRCM; (b) DB in PBO-FRCM; and (c) FR in glass-FRCM.

3.2 Beam Specimens

Table 3 presents a summary of the test results for the RC beam specimens. The load carrying capacity of the FRCM-strengthened beams was generally higher than that of the non-strengthened reference; this demonstrates the successful implementation of FRCM systems in shear-strengthening RC beams. The average improvement in the load carrying capacity was 86.2% for carbon, 39.0% for PBO, and 46.6% for glass FRCM systems. The carbon-FRCM strengthening system showed the most improvement in P_u amongst the three systems, despite it having lower bond capacity than the PBO-FRCM. This can be attributed to the fact that, unlike PBO-FRCM, the failure at the carbon-FRCM/concrete bond occurred not at the concrete/matrix interface, suggesting a better load-transfer mechanism between the RC beam and the FRCM strengthening layer. The effect of the FRCM amount was proved significant, evidently from the fact that the full-strengthened RC beams showed a significantly higher improvement in P_u as compared to those with the intermittent strengthening configuration. Concerning deformational behavior, the deflection at failure (δ_u) for the FRCM-strengthened beams was generally higher than that of the reference. Also, higher values of δ_u were reported for the carbon-FRCM-strengthened beams compared to those with glass- and PBO-FRCM strengthening systems. Finally, the full-length-strengthened beams showed slightly higher values of δ_u compared to those with the intermittent strengthening scheme.

Table 3. Summary of the beam test results.

Specimen	**Fabric type**	**Strengthening pattern**	P_u **(kN)**	**Gain in** P_u **(%)**	δ_u **(mm)**	$\frac{\delta_u}{\delta_{u,ref}}$
R	-	-	104.0	-	3.25	-
C-F	Carbon	Full	209.7	101.6	7.75	2.14
C-I	Carbon	Intermittent	177.6	70.8	7.55	2.13
P-F	PBO	Full	151.3	45.5	5.35	1.65
P-I	PBO	Intermittent	137.7	32.4	4.6	1.42
G-F	Glass	Full	167.9	61.4	6.10	1.88
G-I	Glass	Intermittent	137.0	31.7	4.43	1.36

Figure 3 shows schematic drawings for the crack patterns and failure modes of the tested beams. The reference beam showed a typical shear-failure within the critical span, in which a major crack started at the load point and propagated downwards at approximately 45°. Against this, the FRCM-strengthened beams generally showed an FRCM-debonding mode of failure (mostly observed near the point load). Compared to the intermittent strengthening configuration, the full-length strengthening led to higher ultimate loads because of the large bonded area between the FRCM and concrete substrate. Nonetheless, it was realized that applying the FRCM in an externally-bonded form had not achieved its full strengthening potential: Wakjira and Ebead (2018a, 2018b) reported that near-surface embedding of the FRCM could effectively mitigate the FRCM/concrete deboning and thus maximize the shear-strengthening effectiveness of FRCM.

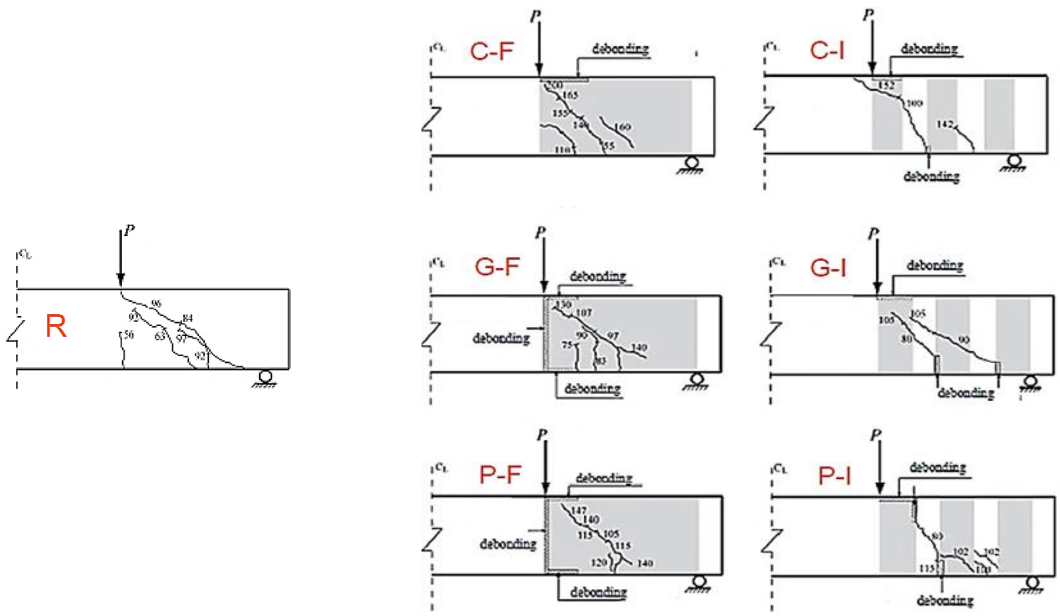

Figure 3. Crack patterns and modes of failure of the tested beams.

4 CONCLUSIONS

This paper investigated the bond and shear-strengthening performance of three FRCM systems. Based on the study results, the following conclusions have been drawn:

- The modes of failure observed in carbon-, PBO-, and glass-FRCM double-shear tests are fabric/matrix debonding, matrix/concrete debonding, and fabric rapture, respectively. Amongst the three systems, the PBO-FRCM showed the highest bond to concrete. The FRCM/concrete bond was observed to improve with an increase in the bond length.
- All strengthened beams were subjected to the same failure mode, namely, debonding at the FRCM/concrete interface. The average gain in the load carrying capacity achieved with FRCM-strengthening was 57%, indicating the successful implementation of FRCM to shear-strengthen RC beams. The full-length strengthening yielded a better strength improvement than that of the intermittent counterpart. Amongst the three systems, carbon-FRCM systems were the most efficient in shear-strengthening RC beams.

Acknowledgments

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