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STRENGTHENING OF RC BEAMS USING NEAR SURFACE EMBEDDED-FRCM

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Fibre reinforced cementitious matrix (FRCM) systems are mostly externally bonded (EB) for the strengthening of reinforced concrete (RC) and masonry structures. In this paper, the relatively new concept of near-surface embedded (NSE) FRCM, has been introduced for the flexural strengthening of beams. The process of the application of NSE-FRCM strengthening technique involves the removal of the concrete layer at beam soffit, being the most deteriorated in actual practices. Experimental evidence of the flexural strengthening efficacy of this technique is provided here. Eight RC beams were prepared and tested under four-point loading with the consideration of two test parameters: (a) FRCM material (polyparaphenylene benzobisoxazole (PBO)/carbon/ glass); and (b) the reinforcement ratio (0.5% representing flexure-deficient beams and 1.28% representing typical under-reinforced beams). The strengthening led to gains in ultimate loads that ranged between 31.4% and 84.3%.

Keywords: Reinforced concrete, Flexure, Repair, Roughening.

1 INTRODUCTION

Research on the strengthening of RC beams deals mostly with new prepared specimens without signs of concrete deterioration (Elghazy *et al.* 2017, 2018a, Pino *et al.* 2017, Tetta *et al.* 2017, Younis *et al.* 2017). This does not simulate real practices where the beams would have suffered deterioration prior to repair or strengthening. This deterioration can be due to steel reinforcement corrosion that leads to degradation in the steel/concrete bond and cross-sectional loss of steel bars (Zhang *et al.* 2018). More 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 the aim of strengthening RC and masonry structures. Researchers focused on the effect of corrosion on the mass loss of steel reinforcement through long-term exposure to severe artificial conditions (Elghazy *et al.* 2018b). The beam soffit is subjected to cracking due to concrete deterioration, and these cracks affect the integrity of the concrete and the concrete/FRCM bond if not addressed. Therefore, any problems in the concrete surface have to be addressed prior to any strengthening work according to the ACI 549 guideline (ACI Committee 549 2013). To better study real applications, some studies tested beams strengthened after being pre-damaged (Ebead 2015) or exposed to accelerated corrosion environments, thus, examined the effect of strengthening corroded beams (Elghazy *et al.* 2017, 2018a). Elghazy *et al.* (2018a) reported on the success of FRCM in the flexural strengthening of corrosion damaged RC beams.

A new concept of substrate roughening, proposed by Wakjira and Ebead, included the removal of the concrete cover and embedding the fabric layers within the created grooves (Wakjira and Ebead 2018a, 2018b). They referred to the installed FRCM system in this technique as near-surface embedded (NSE) FRCM. This technique allows the surface to be prepared without the safety hazards associated with sand blasting. FRCM in the NSE roughening method replaces the damaged concrete preserving the shape and dimensions of the original beam conforming with any architectural restrictions. Moreover, the fact that FRCM is embedded in the concrete cover rather than applied to the surface was reported to also improve the FRCM/concrete interaction for shear strengthened beams (Wakjira and Ebead 2018a). This can be further supported by other research reporting that debonding was observed between the FRCM layer and concrete in beams strengthened with externally bonded FRCM (EB-FRCM) (Younis *et al.* 2017). This NSE roughening technique, however, has not yet been investigated for flexural strengthening.

2 EXPERIMENTAL PROGRAM

The test matrix of the experimental program is given in Table 1. Eight un-strengthened and strengthened RC beams were tested in this study. The beams included flexural-deficient beams (with ρ_s = 0.5%) and typical under-reinforced beams (with ρ_s = 1.28%) strengthened using FRCM with two plies of PBO, carbon, or glass fabrics. The behavior and effectiveness of FRCM with one ply was assessed elsewhere by the authors for characterization tests and EB-FRCM flexural strengthening applications (Ebead *et al.* 2017), and NSE- and EB-FRCM shear strengthening applications (Wakjira and Ebead 2018a, 2018b, Younis *et al.* 2017). The letters ‘P’, ‘C’ and ‘G’ in the beam identification shown in Table 1 refer to PBO, carbon, and glass fabrics, respectively. ‘N’ refers to NSE strengthening. ‘L’ and ‘H’ refer to low and high reinforcement ratios of ρ_s = 0.5% and 1.28%, respectively.

Table 1. Test matrix.

Fabric type	ID	Fabric type	Flexural Reinforcement
1	R-0.5%	-	Low, ρ_s = 0.5%
2	R-1.28%	-	High, ρ_s = 1.28%
3	P-0.5%	PBO	Low, ρ_s = 0.5%
4	C-0.5%	Carbon	Low, ρ_s = 0.5%
5	G-0.5%	Glass	Low, ρ_s = 0.5%
6	P-1.28%	PBO	High, ρ_s = 1.28%
7	C-1.28%	Carbon	High, ρ_s = 1.28%
8	G-1.28%	Glass	High, ρ_s = 1.28%

2.1 Specimens

The geometry and reinforcement details of the test specimens are shown in Figure 1. All beams were 2.5 m long with a rectangular cross-section of 150×260 mm. The tensile steel bars were placed at a depth of 210 mm measured from the top surface of the beam. All beams were reinforced with closed steel stirrups of 8 mm diameter spaced at 100 mm to prevent premature shear failure.

2.2 Test Setup

All beams were four-point loaded at a loading rate of 1 mm/min, which is a common testing speed in static tests (Akbari Hadad *et al.* 2018, Ebead and Marzouk 2002, Wakjira and Ebead 2018a). The beams had an effective span of 2200 mm with shear spans measuring 825 mm as shown in Figure 1. All beams were instrumented with 60 mm strain gauges bonded to the top surface of the concrete in the compression zone and with two 5 mm strain gauges bonded to the tensile steel bars at midspan. Deflections were measured using two linear variable differential transducers (LVDTs) located at midspan.

2.3 Materials

Ready-mixed concrete was used to cast all beams. The concrete proportions per cubic meter were 780 kg of sand, 950 kg of gravel, and 350 kg of ordinary Portland cement with water/cement ratio of 0.45. ASTM C39/C39M (2009) compression tests were conducted on 150×300 mm concrete cylinders revealing an average 28-day compressive strength of 39.5 MPa with a standard deviation of 1.6 MPa. In addition, ASTM C1609 (2012) flexural tests were conducted on six prisms 100×100×500 mm revealing modulus of rupture of concrete of 5.65 MPa with a standard deviation of 0.6 MPa. The yield stress of grade 500B steel bars (ISE/104 Committee 2005) used in this study ranged between 594 and 627 MPa as tested by the authors.

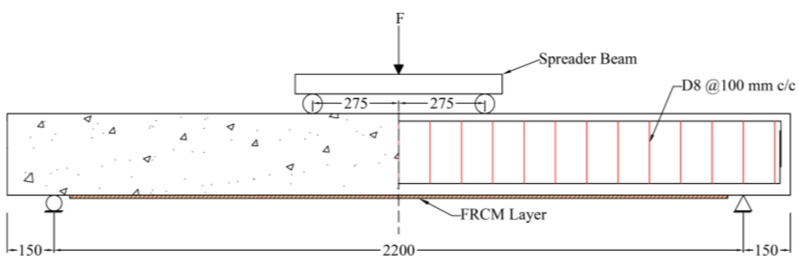


Figure 1. Dimensions and reinforcement details of the longitudinal section of the beams.

Three different types of commercially available FRCM fabrics namely, Carbon, PBO, and Glass were used in this study. The mechanical and geometric properties of each fabric in the warp and weft directions can be found elsewhere (Younis *et al.* 2017). The fabrics were adhered to the concrete surface using their associated mortars as per the manufacturers' recommendations. Mortars had 28-day compressive strengths of 30±2.4, 20±1.4, and 40±2.3 MPa for Carbon-, PBO- and Glass-FRCM, respectively, as tested by the authors according to ASTM C109/C109M (2005) provisions. In addition, FRCM characterization of coupon tests of size 410×50×10 mm was conducted in accordance with AC 434 (ICC (International Code Council) 2016).

2.4 Strengthening Procedure

Prior to FRCM installation for the NSE-FRCM strengthened beams, Group 1 specimens, a 90 mm wide and 15 mm deep groove over the full loaded length of the beam was created using a concrete slitting machine so that the beam did not have the groove at the support location. The depth of the groove was determined as 10 mm for both PBO-FRCM and Carbon-FRCM and 15 mm for Glass FRCM to accommodate the two layers of FRCM plies. The cut concrete was manually chipped off leaving a rough surface as shown in Figures 2a and 2b. The hand lay-up method recommended by ACI 549 (ACI Committee 549 2013) was adopted during the installation of FRCM. The roughened surface was first saturated with water for one hour before applying the first layer of the cementitious matrix with a thickness of 3 to 4 mm. The first fabric ply was then installed in place and was gently impregnated into the matrix as shown in Figure 2c. A second layer of the matrix was immediately applied followed by the second fabric ply and a finishing matrix layer as shown in Figure 2d.

(a) (b) (c) (d)

Figure 2. FRCM Strengthening: (a) grooving the beam, (b) chipping the concrete and clearing the groove, (c) applying first layer of mortar and impregnating the fabric, (d) finishing after FRCM application.

3 RESULTS AND DISCUSSION

Table 2 lists the ultimate loads, P_u, recorded for all beams. Significant gains in the load-carrying capacities were observed in the strengthened specimens. The gain in the load carrying capacity ranged between 31.4% for Specimen G-0.5% and C-1.28% for Specimen C-1.28%. The strengthening effect was more noticeable for specimens with lower reinforced ratio; i.e., the flexure-deficient beams than that for the typical under reinforced counterparts. Specimens with ρ_s= 0.5% showed an increase in P_u that ranged between 31.4% and 57.1% and between 30.1% and 72.8%, respectively, compared to that of the corresponding reference specimen R-0.5%.

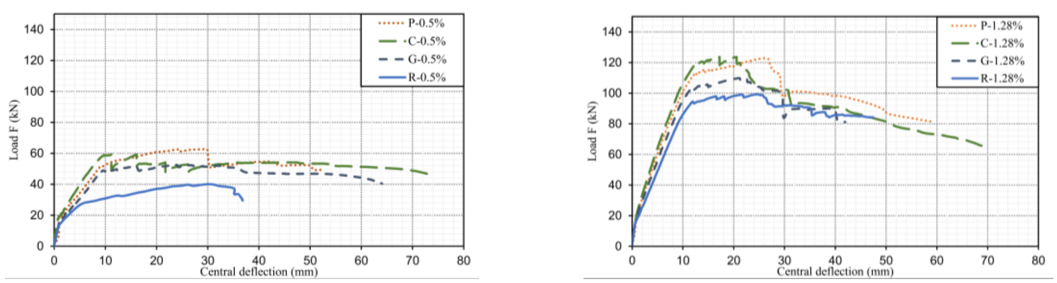
Table 2. Summary of the test results.

Specimen	**ρ_s (%)**	**Initial stiffness, S_I (kN/mm)**	**Post cracking stiffness, S_c (kN/mm)**	**Ultimate capacity, P_u (kN)**	**P_u gain (%)**	**Ductility index,ΔI**
R-0.5%	0.5	15.1	3.53	39.9	-	15.31
	1.28	26.8	7.85	99.2	-	7.31
P-0.5%	0.5	26.8	7.85	62.7	57.1	5.73
C-0.5%	0.5	26.5	5.03	59.2	48.4	3.21
G-0.5%	0.5	16.2	4.11	52.4	31.4	5.56
P-1.28%	1.28	22.9	9.42	123	83.5	3.6
C-1.28%	1.28	23.7	9.74	124	84.3	2.45
G-1.28%	1.28	25.2	8.79	110	70.4	2.87

It was found that both carbon and PBO fabrics provided similar enhancement in the load carrying capacities of the strengthened beams. Specimens strengthened with G-FRCM showed considerably lower strength gains. Specimens with C-, PBO-, and G-FRCM systems showed average gains in the ultimate loads of 1.66, 1.70, 1.51 times the average load capacity of the control specimens. It was observed that G-FRCM strengthened beams presented the highest FRCM fabric utilization. All G-FRCM strengthened beams failed due to fabric rupture.

The load-deflection relationships for the specimens are shown in Figures 3a and 3b. The initial stiffness (S_I) and post cracking stiffness (S_c) are shown in Table 2 for all the tested specimens.

The average S_I for the control beams was 21 kN/mm. This value was increased due to strengthening to 23.6 kN/mm. The average value of S_I was very close to that of the control specimens. The average S_I values for specimens with ρ_s=0.5% (P-0.5%, C-0.5%, and G-0.5%) was 23.2 kN/mm compared to S_I of the control specimen 15.1 kN.mm showing an initial stiffness increase. For higher reinforced (ρ_s=1.28%) NSE specimens (P-1.28%, C-1.28%, and G-1.28%), the average initial stiffness was found to be 23.9 kN/mm that is lower than S_I for the reference specimen R-1.28%. Inspecting the values of the initial stiffness for all NSE specimens shows a slight scatter of the values without a clear trend; however, there are, in average, similar to the average of the reference specimens which is 21 kN/mm. Post crack stiffness, S_c, shows a different behavior to the initial stiffness. The S_c average values were 7.5 kN/mm. The S_c values showed an increase between 12% (Specimen G-1.28%) and 123% (Specimen P-0.5%) compared to their corresponding benchmark Specimens R-0.5% and R-1.28%. The average S_c value for beams with ρ_s=0.5% (P-0.5%, C-0.5%, and G-0.5%) was 5.67 kN/mm. As for the beams with ρ_s=1.27%, all specimens showed similar trend and average at very close values at 9.32 kN/mm. This supports that flexure deficient beams are the most affected in terms of post cracking stiffness by the strengthening scheme.



(a) (b)

Figure 3. Load-Deflection relationships for beams with a) low reinforcement and b) high reinforcement.

The ductility index (ΔI) is defined as the ratio between deflections at the ultimate and yield loads, respectively (Aly *et al.* 2006, Ebead and Saeed 2010, 2013, 2014) and is listed in Table 2. Generally, strengthening lead to a reduction in ΔI when comparing the strengthened beams to their reference counterparts. The strengthened specimens showed an average ΔI that is 35% of that shown by the reference specimens.

4 CONCLUSIONS

Based on the results of this investigation, the following conclusions have been made:

- The average gain in the load carrying capacity was 62.5 % for the strengthened beams.
- It was observed that G-FRCM strengthened beams presented the highest FRCM fabric utilization. All G-FRCM strengthened beams failed due to fabric rupture.
- increase in the initial stiffness was shown for the strengthened specimen with an average of 23.6 kN/mm compared to 21 kN/mm for the reference specimen.

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