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Efficacy of FRCM systems in flexural strengthening of RC T-beams

T G Wakjira[1], **M Afzal**[1], **and U Ebead**[1 *]
[1] Department of Civil and Architectural Engineering, Qatar University, Doha, Qatar
[*] Email: uebead@qu.edu.qa

Abstract. This paper presents an experimental study on the flexural behaviour of RC beams strengthened with fabric reinforced cementitious matrix (FRCM) system. Eight T-shaped RC beams with two different flexural reinforcement ratios (ρ_s=0.40% and ρ_s=1.02%) were constructed and tested as simply supported under monotonic three-point loading. Two beams were kept unstrengthen to act as references while the remaining six beams were strengthened with different types and geometric schemes of FRCM system. Three different test parameters have been considered: (a) FRCM type (carbon and glass), (b) FRCM strengthening scheme (side bonded versus U-shaped scheme), and (c) internal flexural reinforcement ratio. The strengthening system increased the ultimate load carrying capacity by 16.52 – 46.73% in carbon FRCM strengthened beams and 4.84 – 29.41% for glass FRCM strengthened beams relative to the reference beams. The strengthening performance of FRCM system decreased with an increase in the amount of internal flexural reinforcement. Moreover, U-shaped strengthening scheme performed better than the sided bonded counterparts in terms of the gain in the ultimate load and failure modes.

1. Introduction and background

The significance of the strengthening of structural members arises due to their deterioration caused by different factors, e.g., corrosion, end of service life, poor design and/or construction and lack of proper maintenance. In addition, many structures are subjected to service loads higher than the original design load due to the change in the use; hence, structural upgrading to carry the actual service load is required. Moreover, structure may also deteriorate due to its exposure to severe environmental conditions like hurricanes and earthquakes. Thus, an economical and effective means of structural strengthening methods are required. Scholars suggested different methods of strengthening including ferrocement [1,2], steel plates [3], fiber reinforced polymer (FRP) [4–10], and fabric reinforced cementitious matrix (FRCM) [11–15]. Due to its compatibility with both the concrete and masonry substrates and ability to be applied on wet surface, FRCM composite is considered as a viable strengthening solution. The development of FRCM has shown to be effective in structural strengthening of RC structures [16,17] in addition to masonry [18]. Successful applications of FRCM system has been reported for strengthening of RC beams in shear [19–21] and flexure [12,17,22,23].

With the application on the flexural strengthening of RC beams majority of the research work focused on the strengthening of rectangular beams with the use of single fabric types. Moreover, limited literature are available on the effect of varying the amount of internal flexural reinforcement ratio on the efficacy of the FRCM strengthening system [16]. Thus, this paper aims to study the efficacy of FRCM system in flexural strengthening of T-shaped RC beams with two different steel reinforcement ratio and thereby enrich the literature. Two different types of commercially available FRCM systems have been used to strength the beams. The experimental test results have been studied mainly in terms of the load carrying capacity and failure modes.

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2. Experimental program

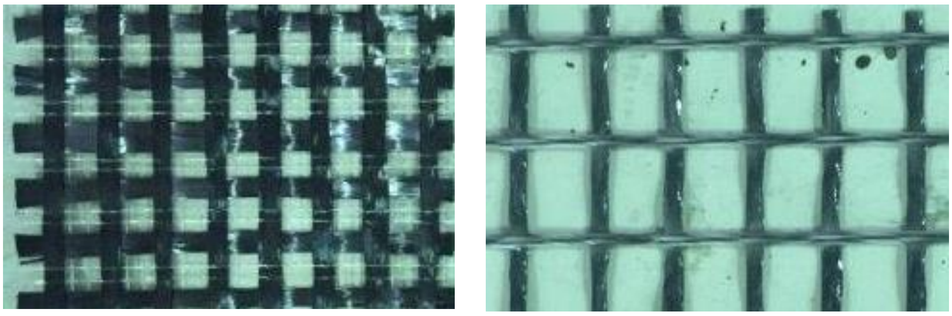
2.1. Material characteristics

The concrete used to cast the beams had an average compressive strength of 30 MPa. The main flexural reinforcement used reinforcement bars with 10 mm and 16 mm diameters while the compressive reinforcement and shear reinforcement used 8 mm diameter bars. The average mechanical properties of the steel reinforcement are given in Table 1.

Table 1. Average mechanical properties of the reinforcement bars.

Bar diameter (mm)	Nominal area (mm^2)	Yield strength (MPa)	Yield strain (%)
8	50.2	535	0.2580
10	78.5	515	0.2660
16	201.1	595	0.2660

The strengthening system used two different types of FRCM composites; viz., carbon and glass. Figures 1a and 1b show the fabric types used in this study. For carbon fabrics, both the warp and weft roving are spaced at 10 mm while in glass fabrics the roving are spaced at 14 mm and 18 mm in the warp and weft directions, respectively. The geometric and average mechanical properties of the fabrics are provided in Table 2 as provided by the manufacturer [24,25]. Both carbon and glass fabrics were used along with their respective mortar types recommended by the manufacturer. The mortar mix for carbon FRCM used 7 liters of water for every 25 kg of mortar while 5 liters of water used for every 25 kg of mortar for glass FRCM as per manufacturer recommendation.



(a) Carbon fabric (b) Glass fabric

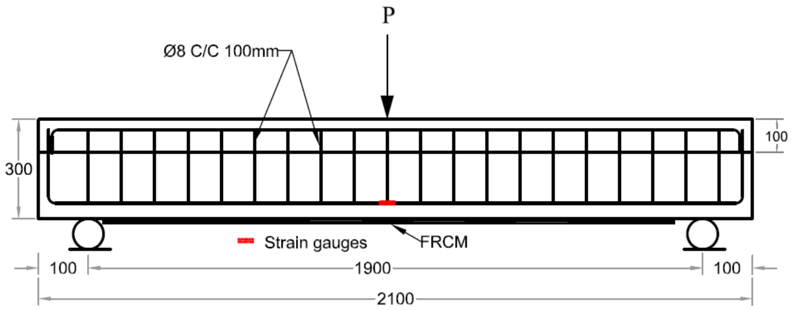
Figure 1. Fabric types used in the study.

Table 2. Geometric and average mechanical properties of the fabrics.

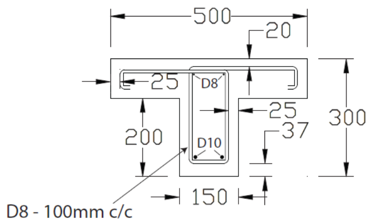
Fabric type	Area per unit width (mm^2/mm)	Elastic Modules (GPa)	Tensile stress (MPa)	Ultimate strain
Glass	0.047	80	2600	0.00325
Carbon	0.047	240	4800	0.00180

2.2. Test beams

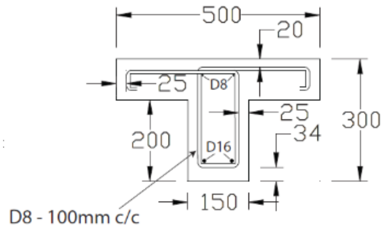
Figures 2a through 2c show the longitudinal and cross-sectional details of beams. Eight medium-scale T-shaped RC beams ($b_w = 150\ mm$, $b_f = 500\ mm$, $h = 300\ mm$ and length of 2100 mm) have been prepared and tested under three-point loading as simply supported system with a clear span of 1900 mm between the supports as shown in Figure 2a. Two different flexural reinforcement ratios have been used (ρ_s = 0.4% and ρ_s = 1.02%) to investigate the effect of internal flexural reinforcement on the flexural performance of FRCM system. The transverse reinforcement involves Ø8 C/C 100 mm.



(a) Longitudinal detail



(b) Cross-sectional detail (ρ_s = 0.4%)



(c) Cross-sectional detail (ρ_s = 1.2%)

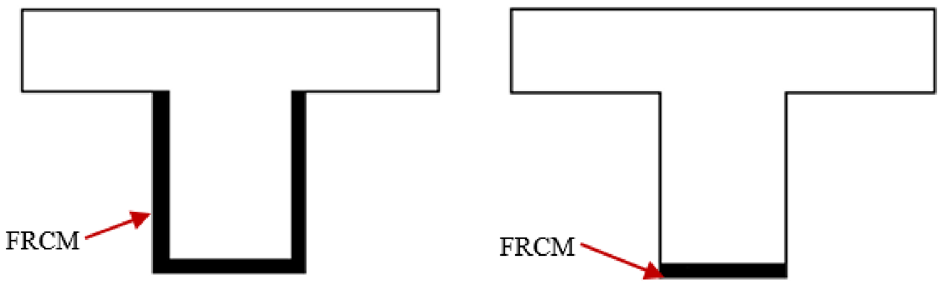
Figure 2. Typical beam details (all dimensions are in mm).

Two beams were kept unstrengthen to act as references while the remaining six beams were strengthened with different FRCM system. The test parameters were as follows:

i. Tensile steel reinforcement ratio: beams with main flexural reinforcement ratio of ρ_s^{D10}= 0.40% and ρ_s^{D16}=1.02%,

ii. Type of FRCM system: carbon FRCM and glass FRCM, and

iii. Strengthening scheme: both U-wrapping (Figure 3a) and side-bonded (Figure 3b) schemes were used.



(a) U-wrapping (b) Side bonded (flat)

Figure 3. Strengthening configuration.

All strengthened beams used two layers of fabrics in the FRCM composite. The nomenclature used to denote the specimens depends on three important parameters; namely, the fabric type (C-for carbon and G- for glass), diameter of tensile reinforcement bar (RD10 and RD16), and strengthening scheme ("F"- for flat or side bonded, "U"- for U-wrapping scheme). Accordingly, G-RD16-U represents a specimen reinforced with 16 mm diameter tensile bars (ρ_s^{D16}=1.02%) and strengthened using two layers of G-FRCM in U-wrapping scheme.

2.3. Test setup
All specimens were tested under three-point flexural test as simply supported system as shown in Figure 4. The test was carried out under displacement-control at a constant deformation of 1 mm/min until failure using Instron Universal Testing Machine along with the measuring devices and gauges. The vertical displacement at the mid-span of the beam was measured using two linear variable displacement transducers placed directly under the loading point on each side of the beam. The strain gauges were used to monitor the strain in the main flexural reinforcement and concrete.

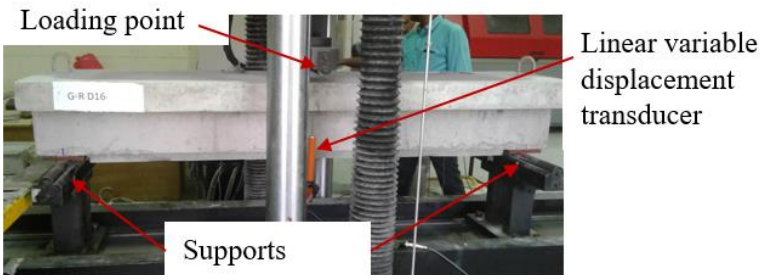


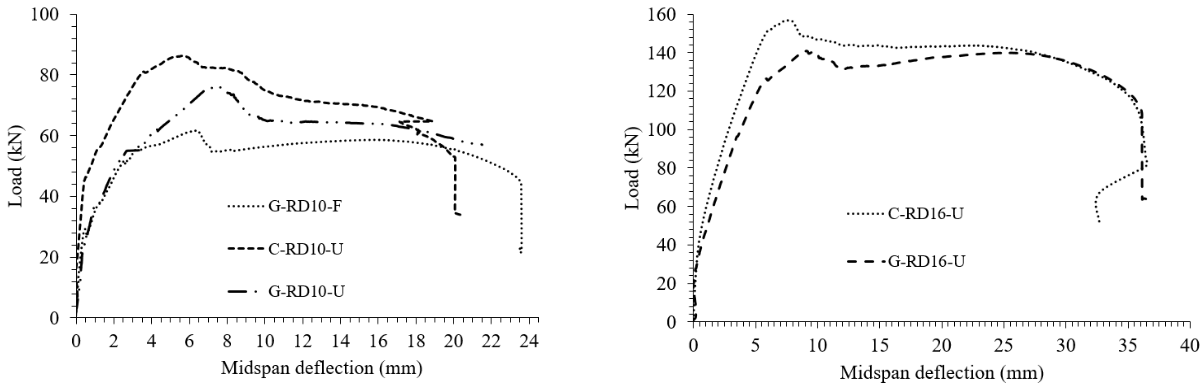
Figure 4. Test setup.

3. Results and discussion
Table 3 provides a summary of the experimental test results in terms of the maximum load carrying capacity (P_{max}) and the gain in P_{max}. Moreover, Figures 5a and 5b show the load versus mid-span deflection for the strengthened beams.

Table 3. Test results.

Beam	ρ_s (%)	FRCM type	P_{max} (kN)	Gain in P_{max} (%)
R10 (reference)	0.40	-	58.77	-
C-RD10-F	0.40	Carbon	78.86	34.19
C-RD10-U	0.40	Carbon	86.24	46.73
G-RD10-F	0.40	Glass	61.62	4.84
G-RD10-U	0.40	Glass	76.06	29.41
R16 (reference)	1.02	-	134.74	-
C-RD16-U	1.02	Carbon	157.00	16.52
G-RD16-U	1.02	Glass	143.56	6.54

In general, the strengthening system had improved the load carrying capacity of the strengthened beams. The highest increase in the ultimate load was observed in Specimen C-RD10-U (46.73%) while a minimum gain in P_{max} of 4.84% was observed in Specimen G-RD10-F as listed in Table 3. The performance of FRCM system varied based on the tested variables. With regard to the FRCM type, carbon FRCM strengthened beams showed higher enhancement in P_{max} compared to that for glass FRCM counterparts as shown in Figures 5a and 5b and Table 3. For example, Specimen, C-RD10-U (46.73%) showed higher enhancement in P_{max} compared to that for its glass FRCM counterpart, G-RD10-U (29.41%). Similarly, Specimens C-RD16-U (16.52%) and C-RD10-F (34.19%) showed higher enhancement in P_{max} compared to that for Specimens G-RD16-U (6.54%) and G-RD10-F (4.84%), respectively as listed in Table 3. As for the strengthening scheme, U-wrapping scheme was more effective than side bonded scheme as shown in Figure 5a and Table 3.

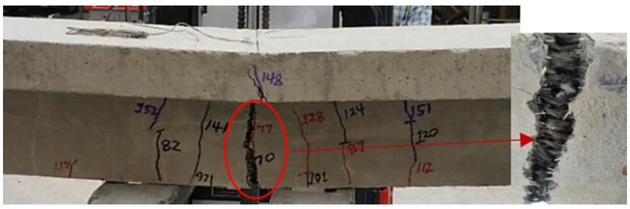


(a) Specimens with $\rho_s = 0.4\%$. (b) Specimens with $\rho_s = 1.02\%$.

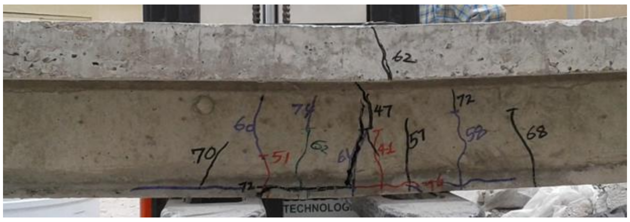
Figure 5. Load versus mid-span deflection under the loading point.

The performance of FRCM system was reduced with the increase in the internal flexural reinforcement ratio. For example, Specimen C-RD10-U failed at an ultimate load of 86.24 kN corresponding to 46.73% increase in the load capacity. Increasing the internal flexural reinforcement ratio from $\rho_s = 0.4\%$ in C-RD10-U to $\rho_s = 1.02\%$ in Specimen C-RD16-U lowered the gain in the load capacity by 30.21%. Similarly, Specimen G-RD16-U (16.52%) showed lower enhancement in P_{max} compared to that of Specimen G-RD10-U (29.41%).

The type of failure mechanism varied based on the strengthening scheme. The failure in the specimens strengthened with U-wrapped scheme was generally characterized by fabric slippage within the FRCM as shown in Figure 6a for Specimen C-RD10-U. On the other hand, specimens strengthened with side-bonded strengthening scheme generally failed due to debonding of FRCM from the substrate concrete as shown in Figure 6b.



(a) C-RD10-U



(b) G-RD10-F

Figure 6. Crack pattern and failure modes.

4. Conclusion

This paper presents an experimental study on the flexural strengthening performance of FRCM system. Eight medium-scale T-shaped RC beams were used for this purpose considering three different test parameters: (a) FRCM type, (b) strengthening scheme, and (c) amount of internal flexural reinforcement. The test results showed that FRCM is effective in strengthening of RC beams in flexure with the strengthening efficacy that varied based on the tested parameters. The following conclusions have been drawn from the experimental results.

- The strengthening system was effective in enhancing the load carrying capacity of the strengthened T-beams. The percentage enhancement in the load capacity of up to 46.73% has been observed.
- With regard to the type of the composite, carbon FRCM was more effective than glass FRCM in enhancing the load capacity of the strengthened beams.
- As of the strengthening scheme, U-wrapped scheme showed better performance than that of side bonded.
- The efficacy of the FRCM system decreased with the increase in the internal flexural reinforcement ratio.
- Generally, FRCM debonding from the concrete substrate governed the failure of sided bonded FRCM specimens while U-wrapping scheme was associated with fabric slippage within the FRCM composite.

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