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FRCM SHEAR STRENGTHENING FOR CONCRETE BEAMS

ADEL YOUNIS[1], USAMA EBEAD[1], and KSHITIJ C. SHRESTHA[2]

[1]*Dept of Civil and Architectural Engineering, Qatar University, Doha, Qatar*
[2]*Institute of Industrial Science, University of Tokyo, Tokyo, Japan*

This paper presents the results of an experimental study carried out to examine the efficacy of Fabric-Reinforced Cementitious Matrix (FRCM) in strengthening RC beams susceptible to shear failure. In this paper, seven shear-critical RC beams, of 2,500 mm in length, 150 mm in width, and 330 mm in depth, were tested under three-point loading until failure. Two main test variables were considered, which are: a) Strengthening material: carbon, polyparaphenylene benzobisoxazole (PBO), or glass FRCM, and b) Strengthening application pattern: a single full-length FRCM plate or a set of intermittent and spaced FRCM strips were applied along the critical shear zone. The test results confirmed the efficacy of FRCM strengthening in improving the load capacity of shear-critical RC beams. The FRCM-strengthening contributed to increases in the load capacity ranged between 31% and 100% compared to the reference specimen. The full-length strengthened specimens generally showed a better strength enhancement compared to the intermittent counterparts when using the same FRCM material. Such intuitive observation assures the importance of the amount of strengthening material applied in the critical shear zone. Besides, specimens utilizing carbon fibers in its FRCM strengthening material showed the highest strength enhancement among the three systems.

Keywords: Rehabilitation, Repair, Structures, Shear strength, Experimentation, Load-carrying capacity, Strengthening scheme.

1 INTRODUCTION

Fabric reinforced cementitious matrix (FRCM) is a strengthening system for reinforced concrete (RC) and masonry structures, recently introduced in the literature as an alternative to the traditional externally bonded fiber-reinforced polymer (FRP) systems (Ebead *et al.* 2016a, 2016b, Elghazy *et al.* 2016, Pino *et al.* 2016). In the past two decades, there has been a growing research interest towards FRCM systems due to their ability to resist extremely high temperatures as well as the possibility to use recycled materials in them (Awani *et al.* 2017). Moreover, the application of FRCM system involves using inorganic cement–based mortar as a binding agent, which is well-matched with the original concrete substrate (D'Ambrisi *et al.* 2013). Therefore, FRCM is considered as a strengthening solution in the regions of possible fire hazards, extreme humidity, and high chloride exposure that can be severely deteriorative to RC structures. More often than not, construction and rehabilitation industry have also been attracted to the FRCM systems for repairing and strengthening concrete and masonry structures (ACI Committee 549 2013). FRCM is regarded as a viable alternative to the externally-bonded fiber reinforced polymer strengthening technique that has been presented in several research contributions (Baky *et al.* 2007, Ebead 2011, Ebead and Marzouk 2004, Ebead and Saeed 2014, Elsayed *et al.* 2009, Kotynia *et al.* 2008, Neale *et al.* 2011).

Successful applications of FRCM system for strengthening RC structures have been reported in the previous research. The efficiency of FRCM strengthening technique has been investigated in a wide range of applications including strengthening of RC slabs in flexure (Loreto *et al.* 2013), RC column strengthening (Ombres and Verre 2015), and strengthening of RC beams critical either in shear (Loreto *et al.* 2015) or in flexure (Ebead *et al.* 2016b). In general, these studies reported that the members strengthened with FRCM exhibited a significant improvement in the structural capacity and performance when compared to the non-strengthened specimens.

In this study, it is aimed to investigate the performance of Fabric-Reinforced Cementitious Matrix in strengthening RC beams critical in shear. At the outset, the experimental program will be explained comprising the description of materials, RC beam specimens, strengthening procedure, test setup, and instrumentation. After that, the experimental results of this effort will be presented and discussed, mainly for the load-carrying capacity and deformational characteristics of the tested specimens.

2 EXPERIMENTAL PROGRAM

2.1 Materials

Ready-mixed concrete was used to cast the beam specimens. Compression test conducted on concrete cylinders, of 150 mm in diameter and 300 mm in height, revealed an average 28-day strength of 30 MPa. Grade 500B (BS 4449:2005) steel bars were used reinforces the concrete beam specimens. Bars of 8 mm in diameter were used as transverse reinforcement in the non-critical shear zone of the beam, while 16 mm diameter bars were used as main flexural reinforcement. Based on a tested sample of the bars used, the yield stress, yield strain, and modulus of elasticity are measured to be 595 MPa, 0.266%, and 224 GPa, respectively.

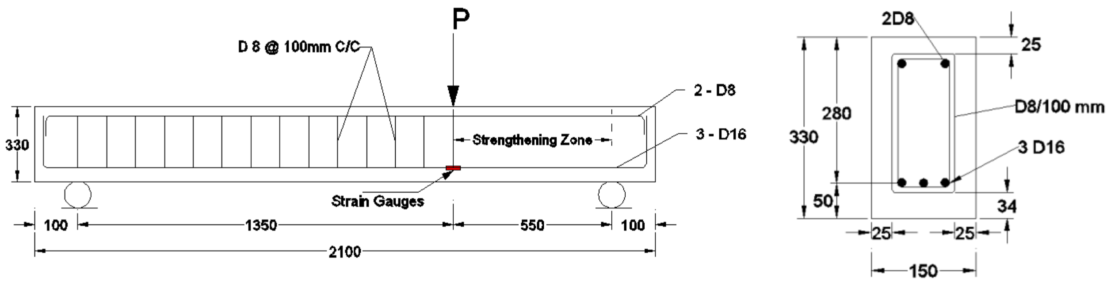
Three different types of commercially available FRCM systems were used in this study, namely: Carbon-FRCM (Ruredil 2016a), polyparaphenylene benzobisoxazole (PBO)-FRCM (Ruredil 2016b), and Glass-FRCM (SIKA 2016). Each fabric type was mixed with its associated mortar matrix as per manufacturers' recommendations in order to form the corresponding FRCM system. Table 1 lists the mechanical properties of each fabric type, along with the 28-day compressive strength of the corresponding mortar, provided by the manufacturers.

Table 1. Properties of fabric (in the warp direction) and mortars corresponding to the FRCM systems.

Fabric type	Area per unit width, A_f (mm^2/mm)	Elastic modulus (GPa)	Tensile strength (GPa)	Ultimate strain (%)	Compressive strength of mortar (MPa)
PBO	0.045	270	5.80	2.15	30
Carbon	0.047	240	4.8	1.8	20
Glass	0.047	80	2.6	3.25	40

2.2 RC Beam Specimens

A total of seven reinforced concrete critical in shear beams (2,500 mm in length, 150 mm in width, and 330 mm in depth) were tested. One non-strengthened beam was used as a benchmark specimen, while the other beams had different strengthening schemes and configurations. Figure 1 shows a typical longitudinal and mid-span section for the beams without strengthening.



(a) Longitudinal section. (b) Mid-span cross section.

Figure 1. Typical longitudinal and mid-span sections for the RC beam specimens before strengthening.

Two test variables were considered, which are: a) FRCM system (Carbon, PBO, or Glass); and b) strengthening pattern: a single full-length FRCM plate or a set of intermittent and spaced FRCM strips were applied along the critical shear zone. It should be noted that, for the intermittent strengthening pattern, the strengthening system was applied within the critical shear span by a set of 120 mm wide FRCM strips with a typical space of 95 mm in between, yielding a partially strengthened length of 360 mm out of the 550 mm critical shear span. Table 2 shows the test matrix for the beam specimens.

Table 2. Characteristics of the beam specimens.

Designation	Textile material	Strengthening pattern	Strengthening orientation
Reference	-	-	-
C-Full	Carbon	Full	90º
C-Intermittent	Carbon	Intermittent	90º
P-Full	PBO	Full	90º
P-Intermittent	PBO	Intermittent	90º
G-Full	Glass	Full	90º
G-Intermittent	Glass	Intermittent	90º

The FRCM system applied on each side of the strengthened beam consisted of: (a) an internal layer of 5 mm thick mortar applied after roughening the concrete surface on the beam sides, (b) the first layer of fabric corresponding to the FRCM type, (c) an intermediate layer of mortar of 2-3 mm in thickness, applied on top of the fabric layer, (d) the second layer of fabric, and (e) an external layer of 5 mm thick mortar.

2.3 Test Setup and Instrumentation

The Instron 1500HDX Static Hydraulic Universal Testing machine, located in the Structures Laboratory of Qatar University, was used to test the beams under three-point loading. The beams were placed on the testing machine along with the measurement instruments and the data acquisition system. Displacement-controlled loading was applied at a rate of 1 mm/min on the tested beams until failure. During the test, the mid–span deflection was measured at each load step by a Linear Variable Displacement Transducer (LVDT). Moreover, two strain gauges of 5 mm gauge length and 5% maximum strain limit were attached to the flexural reinforcement bars at the location below the loading point (P) as shown in Figure 1. Data acquisition of the measurements was performed at a frequency of 1Hz.

3 RESULTS AND DISCUSSION

Table 3 presents a summary of the beam test results. For each specimen, the ultimate load-carrying capacity (P_u) and the gain in P_u compared to the reference specimen are listed in the second and third columns, respectively. Regarding the deflection results, the fourth column lists the deflection values at failure (δ_u), and the fifth column shows the increase in δ_u with respect to the reference specimen. Lastly, the sixth column presents the flexural reinforcement strain measured at the ultimate load (ε_s).

Table 3. Summary of the test results.

Beam Identifier	P_u (kN)	Gain in P_u (%)	δ_u (mm)	Gain in δ_u (%)	ε_s (%)
Reference	104.0	-	3.25	-	0.143
C-Full	209.7	101.6	7.75	138.5	0.286
C-Intermittent	177.6	70.8	7.55	132.3	0.224
P-Full	151.3	45.5	5.35	64.6	0.195
P-Intermittent	137.7	32.4	4.6	41.5	0.170
G-Full	167.9	61.4	6.10	87.7	0.197
G-Intermittent	137.0	31.7	4.43	36.3	0.175

3.1 Load-Carrying Capacity

The ultimate load-carrying capacity showed an improvement for the FRCM-strengthened specimens compared to the reference beam (where $P_u = 104\ kN$), indicating the successful application of the FRCM-strengthening system to enhance the capacity of RC beams critical in shear. The average gain in load-carrying capacity after strengthening was 86.2, 39.0, 46.6% for carbon, PBO, and glass FRCM systems, respectively. Figures 2(a), (b), and (c) present the load versus mid-span deflection diagrams for three sets of specimens with carbon, PBO, and glass - FRCM systems, respectively.

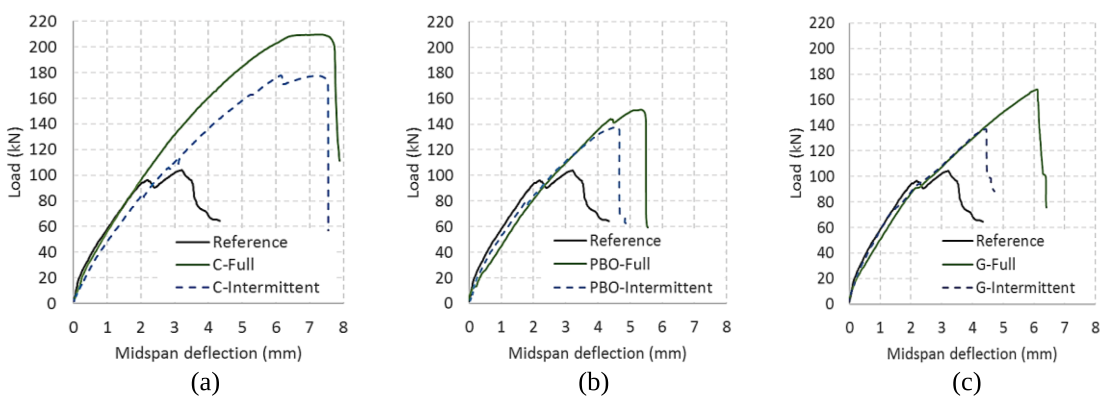


Figure 2. Load-deflection plots for the beams strengthened with (a) Carbon-FRCM, (b) PBO-FRCM, and (c) Glass-FRCM systems.

The Carbon-FRCM strengthening system generally exhibited a better enhancement in P_u than the PBO- and Glass-FRCM systems. In addition, the beams with full-length strengthening scheme reported significantly higher gains in P_u compared to those with the intermittent counterpart. This demonstrates the importance of the amount of strengthening material applied within the critical shear span. Moreover, utilizing the carbon FRCM strengthening technique was more effective in increasing the ultimate load carrying capacities of the beams compared to the PBO and glass counterparts.

3.2 Deformational Characteristics

As mentioned before, the mid-span deflection was measured at each load step until failure occurs. The mid-span deflection at failure, denoted by δ_u, generally showed increment for the FRCM-strengthened beams compared to the benchmark (of which $\delta_u = 3.25\ mm$). Carbon-FRCM strengthened beams showed a higher value of δ_u compared to Glass and PBO counterparts, which indicates a better deformational performance for the beams strengthened with Carbon-FRCM system. For instance, the C-Full specimen has a measured value of 7.75 mm for δ_u, which is higher than the values recorded for P-Full ($\delta_u = 5.35\ mm$) and G-Full ($\delta_u = 6.10\ mm$). Moreover, the specimens with full-length strengthening scheme reported slightly higher values of δ_u compared to the intermittent counterparts. As an example, the P-Intermittent specimen shows a value of 4.6 mm for δ_u, which is smaller than that for P-Full ($\delta_u = 5.35\ mm$).

Regarding strain characteristics, all beam specimens failed before yielding of the flexural reinforcement ($\varepsilon_s < \varepsilon_y = 0.266\%$), except for C-Full, which has crushed just after the yield tensile strain, was reached. Bearing in mind that concrete crushing has not been observed at the top surface of any specimen, this confirms that the beams were subjected to the shear type of failure as originally purposed in the design stage. In addition, the flexural reinforcement strain reached at failure for the FRCM-strengthened beams was generally more than that for the reference specimen, indicating the successful use of the strengthening system in mitigating the brittle shear failure by allowing the main steel to 'move' a step closer towards the yield region.

4 CONCLUSION

This study has experimentally investigated the efficacy of Fabric-Reinforced Cementitious Matrix in strengthening RC beams critical in shear. A total of 7 RC beam specimens were tested under three-point loading until failure. Two test parameters were considered, namely: the strengthening material and the continuity of strengthening within the critical shear span. The test results confirmed the successful use of FRCM strengthening to enhance the load capacity of shear-critical RC beams. In general, there was an improvement in the load-carrying capacity of the FRCM-strengthened beams ranged between 31% and 100% compared to the benchmark. Moreover, a better strength enhancement was observed for the full-length strengthening scheme than the intermittent counterpart when using the same FRCM material. In addition, carbon FRCM system was more effective than PBO and glass FRCM counterparts in enhancing the load capacity of the strengthened beams.

Acknowledgments

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References

ACI Committee 549, *Guide to Design and Construction of Externally Bonded Fabric-reinforced Cementitious Matrix (FRCM) Systems for Repair and Strengthening Concrete and Masonry Structures (ACI 549.4R-13)*, American Concrete Institute, Farmington Hills, MI, USA, 2013.

Awani, O., El-Maaddawy, T., and Ismail, N., Fabric-reinforced Cementitious Matrix: A Promising Strengthening Technique for Concrete Structures, *Construction and Building Materials*, Elsevier, 132, 94–111, 2017.

Baky, H. A., Ebead, U. A., and Neale, K. W., Flexural and Interfacial Behavior of FRP-strengthened Reinforced Concrete Beams, *Journal of Composites for Construction*, American Society of Civil Engineers, 11(6), 629–639, 2007.

D'Ambrisi, A., Feo, L., and Focacci, F., Experimental Analysis on Bond Between PBO-FRCM Strengthening Materials and Concrete, *Composites Part B: Engineering*, Elsevier, 44(1), 524–532, 2013.

Ebead, U., Hybrid Externally Bonded/Mechanically Fastened Fiber-reinforced Polymer for RC Beam Strengthening, *ACI Structural Journal*, American Concrete Institute, 108(6), 669, 2011.

Ebead, U. A., Shrestha, K. C., Afzal, M. S., Refai, A. E., and Nanni, A., Effectiveness of FRCM System in Strengthening Reinforced Concrete Beams, *Proceedings of the 4th International Conference in Sustainable Construction Materials and Technologies (SCMT4)*, University of Nevada, Las Vegas, 2016a.

Ebead, U., and Marzouk, H., Fiber-reinforced Polymer Strengthening of Two-way Slabs, *ACI Structural Journal*, 101(5), 650–659, 2004.

Ebead, U., and Saeed, H., Flexural and interfacial behavior of externally bonded/mechanically fastened fiber-reinforced polymer-strengthened reinforced concrete beams, *ACI Structural Journal*, American Concrete Institute, 111(4), 741–751, 2014.

Ebead, U., Shrestha, K. C., Afzal, M. S., El Refai, A., and Nanni, A., Effectiveness of Fabric-reinforced Cementitious Matrix in Strengthening Reinforced Concrete Beams, *Journal of Composites for Construction*, American Society of Civil Engineers, 4016084, 2016b.

Elghazy, M., Refai, A. E., Ebead, U. A., and Nanni, A., Performance of Corrosion-aged Reinforced Concrete (RC) Beams Rehabilitated with Fabric-reinforced Cementitious Matrix (FRCM), *Proceedings of the 4th International Conference in Sustainable Construction Materials and Technologies (SCMT4),* University of Nevada, Las Vegas, 2016.

Elsayed, W. E., Ebead, U. A., and Neale, K. W., Mechanically Fastened FRP-strengthened Two-way Concrete Slabs With and Without Cutouts, *Journal of Composites for Construction*, American Society of Civil Engineers, 13(3), 198–207, 2009.

Kotynia, R., Abdel Baky, H., Neale, K. W., and Ebead, U. A., Flexural Strengthening of RC Beams with Externally Bonded CFRP Systems: Test Results and 3D Nonlinear FE Analysis, *Journal of Composites for Construction*, American Society of Civil Engineers, 12(2), 190–201, 2008.

Loreto, G., Babaeidarabad, S., Leardini, L., and Nanni, A., RC Beams Shear-strengthened With Fabric-Reinforced-cementitious-matrix (FRCM) Composite, *International Journal of Advanced Structural Engineering (IJASE)*, Springer, 7(4), 341–352, 2015.

Loreto, G., Leardini, L., Arboleda, D., and Nanni, A., Performance of RC Slab-type Elements Strengthened With Fabric-reinforced Cementitious-matrix Composites, *Journal of Composites for Construction*, American Society of Civil Engineers, 18(3), A4013003, 2013.

Ombres, L., and Verre, S., Structural Behaviour of Fabric Reinforced Cementitious Matrix (FRCM) Strengthened Concrete Columns Under Eccentric Loading, *Composites Part B: Engineering*, Elsevier, 75, 235–249, 2015.

Neale, K., Godat, A., Baky, H. A., Elsayed, W., and Ebead, U., Approaches for finite element simulations of FRP-strengthened concrete beams and slabs, *Architecture Civil Engineering Environment*, 4(4), 59–72, 2011.

Pino, V., Hadad, H. A., De Caso, F., Nanni, A., Ebead, U. A., and El Refai, A., *Performance of FRCM Strengthened RC Beams Subject to Fatigue*, 2016.

Ruredil, *Technical datasheet,* Ruredil X mesh C10 data sheet, 2016a.

Ruredil, *Technical datasheet,* Ruredil X mesh gold data sheet, 2016b.

SIKA, *Technical datasheet*, SikaWrap-350G Grid data sheet, 2016.