Responsible Design and Delivery of the Constructed Project
Edited by Abdul-Malak, M., Khoury, H., Singh, A., and Yazdani, S.

ISBN: 978-0-9960437-5-5

EFFECTIVENESS OF FRCM SYSTEM IN STRENGTHENING RC BEAMS IN SHEAR USING HYBRID NSE/EB TECHNIQUE

USAMA EBEAD and TADESSE WAKJIRA

Dept of Civil and Architectural Engineering, College of Engineering, Qatar University, Doha, Qatar

This paper presents an experimental study on the efficacy of a recently introduced hybrid "near surface embedded/ externally bonded" NSE/EB fabric reinforced cementitious matrix (FRCM). Seven medium scale RC beams, deficient in shear, were constructed and tested under three-point loading. Six beams were strengthened using hybrid NSE/EB-FRCM technique and one beam was left un-strengthened as a reference. Two main test variables were considered; viz., strengthening configuration: full versus intermittent strengthening configuration and FRCM type: glass FRCM versus polyparaphenylene benzobisoxazole (PBO). The test results revealed that the hybrid NSE/EB-FRCM strengthening technique is effective in enhancing the shear capacity of the strengthened beams. The strengthened specimens showed an average of 67% higher shear capacity relative to the reference specimen. With regard to the FRCM type, G-FRCM strengthened specimens showed an average of 73% enhancement in the shear capacity, which was 12% higher than the value for PBO-FRCM counterpart. Moreover, the strengthened beams showed higher deflection at the ultimate load than that of the reference specimen. Furthermore, the hybrid NSE/EB-FRCM technique has shown to be a promising alternative to the conventionally used externally bonded FRCM system with the potential to reduce the debonding of FRCM from the concrete substrate.

Keywords: Rehabilitation, Near surface embedded/externally bonded, Fabric reinforced cementitious matrix (FRCM), Reinforce concrete (RC) beam.

1 INTRODUCTION

As a result of structural deterioration caused by different factors (e.g. corrosion of steel bars, end of life, change in service load, and severe environmental conditions), there is a need for developing strengthening methods that can increase their capacity hence extend their life time (Younis *et al.* 2017a). Different methods have been used for the strengthening of the deteriorated structural members. Some of these methods include steel plates (Ebead and Marzouk 2002a, 2002b), ferrocement (Ebead 2015), fiber reinforced polymer (FRP) composites (Ebead and Marzouk 2004, Ebead and Saeed 2014, 2017, Elsayed *et al.* 2009, Kotynia *et al.* 2008), and fabric reinforced cementitious matrix (Elghazy *et al.* 2017, Pino *et al.* 2017, Younis *et al.* 2017b). FRP composites are widely used as a strengthening material due to their favorable behavior over traditional strengthening system. Some of the advantages of FRP composites include the ease and speed of application, resistance to corrosion, high strength to weight ratio, and light weight (Aly *et al.* 2006).

Despite their relative efficiency to the traditional strengthening method FRP composites possess some drawbacks; e.g., incompatibility with the concrete substrate, susceptibility to failure at high temperature and difficulty to apply on wet surface (Raoof and Bournas 2017). To overcome some of these problems, cement-based FRCM composites have recently been developed by replacing the epoxy adhesive with cementitious matrix and fibres with textile fabrics (Trapko *et al.* 2015). FRCM has better adherence with the substrate concrete. In addition to this, FRCM composites possess good resistance to elevated temperature and fire (Raoof and Bournas 2017, Tetta and Bournas 2016). FRCM composites have been used for the strengthening of beams both in flexure and shear (Ombres 2015, Tetta *et al.* 2015, Younis *et al.* 2017c) by externally bonding the material on the surface of the concrete. However, externally bonded FRCM (EB-FRCM) technique is associated with debonding of FRCM off the substrate concrete limiting the utilization of the material (Panigrahi *et al.* 2014, Wakjira and Ebead 2018, Younis *et al.* 2017a). As a remedy to this problem, the authors introduced hybrid "near surface embedded/externally bonded FRCM" technique as a viable alternative to EB-FRCM technique.

Thus, the paper aimed at studying the efficacy of NSE/EB-FRCM technique for the shear strengthening of RC beams. The experimental program involved the construction and testing of seven medium scale RC beams, deficient in shear. The test results are discussed in terms of the shear capacity, deformational characteristics, and failure modes.

2 EXPERIMENTAL PROGRAM

2.1 Material Properties

The beam specimens were cast using ready-mixed concrete with an average compressive strength of 30 MPa. The internal flexural tensile reinforcement used 16 mm diameter steel bars while 8 mm diameter steel bars were used as longitudinal compressive reinforcement and stirrups. Table 1 provides the average mechanical properties of the steel reinforcement.

Table 1. Mechanical properties of the reinforcement steel bars.

Bar diameter (mm)	Yield strength (MPa)	Yield strain (με)	Modulus of elasticity (GPa)
8	535	2580	207
16	595	2660	224

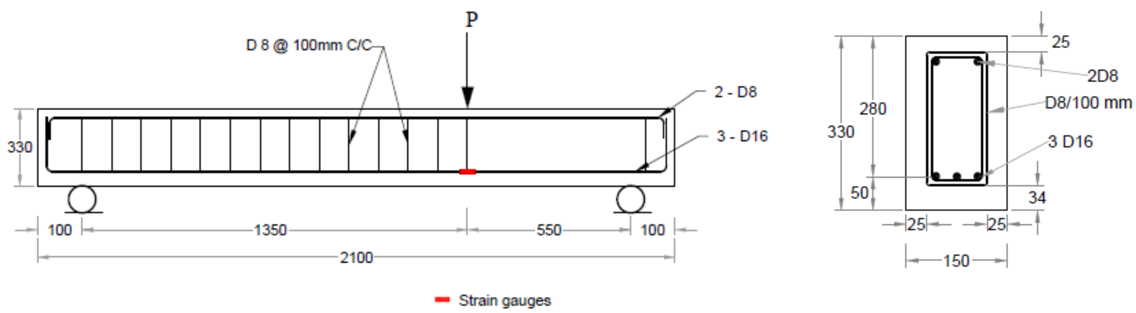
The strengthening technique used two different fabric types; namely, glass and PBO fabric with their associated mortar type as recommended by the manufacturer. The geometric and mechanical properties of the fabrics are summarized in Table 2.

Table 2. Geometric and mechanical properties of the fabrics.

Fabric type	Area per width in the warp direction (mm^2/mm)	Area per width weft direction (mm^2/mm)	Modulus of elasticity (MPa)	Tensile stress (MPa)	Ultimate strain (με)
Glass	0.047	0.066	80000	2600	32500
PBO	0.045	0.0155	270000	5800	21500

2.2 Test Beam

Six specimens were strengthened with different configuration of NSE/EB-FRCM technique, while one beam without strengthening was used as a reference. The dimension and reinforcement details of the reference specimen is shown in Figures 1a and 1b that show the longitudinal detail and cross-sectional detail of the beam, respectively.



(a) (b)

Figure 1. Specimen detail: (a) longitudinal detail and (b) cross-sectional detail outside the shear span (all dimensions are in mm).

The NSE/EB-FRCM technique utilized two layers of near surface embedded (NSE) FRCM and two layers of externally bonded FRCM system. The strengthening system involved: (a) preparation of the grooves (for the NSE part), and (b) application of first layer of the mortar followed by installation of first, second, third and fourth layer of fabrics by keeping an average of 3 mm thickness of mortar between each layers of fabrics. Finally, surface finishing was done using a trowel and the specimens were cured for a minimum of 28 days prior to testing.

Table 3 lists the test matrix with two main test variables being studied; viz., (a) fabric type: glass versus PBO fabric, and (b) strengthening configuration: both full and intermittent configuration was used for both NSE part and EB part. Intermittent FRCM configuration involved strips of 120 mm wide at 95 mm spacing. The specimen nomenclature for the strengthened beams includes three letters in which the first letter represents the fabric type, the second and last letter represent the strengthening scheme for NSE and EB FRCM part, respectively as listed in Table 3.

Table 3: Test matrix.

Specimen Identifier	**Type of fabric**	**Strengthening configuration**	
		NSE part	**EB part**
*R	-	-	-
PFF	PBO	Full	Full
PIF	PBO	Intermittent	Full
PII	PBO	Intermittent	Intermittent
GFF	Glass	Full	Full
GIF	Glass	Intermittent	Full
GII	Glass	Intermittent	Intermittent

*R-reference beam

2.3 Test Setup and Instrumentation

The experimental work was carried out under three-point loading as a simply supported system. The displacement under the loading point was measured using linear variable displacement transducers (LVDT). The strain in the concrete was measured using concrete strain gauge with maximum strain limit of 0.2% and gauge length of 60 mm. Moreover, a strain gauge with 5% strain limit and 5 mm length was used to monitor the strain in the tensile reinforcement bars.

3 RESULTS AND DISCUSSION

Table 4 summarized the test results in terms of the maximum load capacity (P_u), deflection at the peak load (Δ_u), and strain values.

Table 4. Experimental test result summary.

Specimen Identifier	P_u (kN)	Gain in P_u (%)	Δ_u (mm)	Increase in Δ_u (%)	$\varepsilon_{s,u}$ (%)	$\varepsilon_{c,u}$ (%)
R	104	-	3.25	-	0.14	-
PFF	183	76	6.41	97	0.25	0.18
PIF	170	63	6.3	94	0.19	0.13
PII	150	45	5.38	66	0.22	0.13
GFF	187	80	7.44	129	0.26	0.16
GIF	185	78	6.24	92	0.21	0.12
GII	168	61	5.71	76	0.22	0.2

3.1. Shear Capacity

The hybrid NSE/EB-FRCM system has significantly enhanced the shear capacity of the strengthened beams relative to that of the reference specimen (R). The gain in the shear capacity was provided in the third column of Table 4. The mean gain in the shear capacity was 67%, which shows a successful implementation of the hybrid NSE/EB-FRCM technique for strengthening of shear deficient RC beams. The maximum enhancement in the shear capacity was observed in Specimen GFF strengthened with glass NSE/EB-FRCM involving full configuration for both NSE and EB part.

Generally, glass FRCM showed higher enhancement in the shear capacity than that for the PBO FRCM counterparts as listed in Table 4. For instance, the gain in the shear capacity for Specimen GIF was 78%, which was 15% higher than its PBO-FRCM counterpart, PIF (63%) as listed Table 4. Moreover, the full NSE/EB-FRCM configuration showed a higher shear capacity than that for the intermittent FRCM configuration. For instance, the gain in the shear capacity for Specimen GFF, which was strengthened with full NSE/EB-FRCM for both NSE and EB parts, was 76% as listed in Table 4. Altering the NSE configuration to intermittent strips lowered the gain in the shear capacity to 63%. This gain was further reduced to 45% for Specimen PII, strengthened with intermittent configuration for both NSE and EB parts. These results confirmed the significance of the amount of FRCM system in the shear span.

3.2. Deformational Characteristics

The deflection under the loading point at the maximum load (Δ_u) was given in the fourth column of Table 4 while the fifth column of the same table provides the increase in Δ_u relative to the reference beam. The average increase in deflection at the peak load was 99% for the G-FRCM specimen while it was 85% for the PBO-FRCM specimens relative to the reference beam. With regard to the strengthening scheme, the full NSE/EB-FRCM configuration showed higher deflection at the maximum load than that for the intermittent configuration. For instance, the Δ_u value for specimen GFF (7.44 mm) was higher than for Specimen GIF (6.24 mm) which was in turn higher than the value for Specimen GII (5.71 mm).

With regard to the strain values, all beams failed before flexural steel reaches its yielding point as listed in the sixth column of Table 4 and concrete did not reach its crushing point as listed in the last column of Table 4. Thus, the beams failed in shear as expected. Moreover, the hybrid NSE/EB-FRCM system has increased the strain values in flexural steel bars as listed in Column 6 of Table 4, which indicates that the strengthening system has delayed the brittle type of shear failure so that the flexural bars showed more tensile strains.

4 CONCLUSION

In this paper, the efficacy the NSE/EB-FRCM system for strengthening of RC beams in shear has been presented. The experiment work was carried out on seven (7) medium scale RC beams deficient in shear tested under three-point loading. Two different FRCM types were utilized; namely, glass and PBO FRCM. The test parameters were: (a) type of FRCM composite and (b) strengthening configuration. The NSE/EB-FRCM system has successfully increased the shear capacity of the beams. The percentage gain in the shear capacity ranged between 45% and 76% for PBO-FRCM system while it ranged between 61% and 80% for glass FRCM system. Specimens strengthened with G-FRCM system showed higher enhancement in the shear capacity compared to that for the PBO FRCM counterparts. The average increase in the deflection at the peak load were 85% and 99% for G- and PBO-FRCM relative to the reference specimen, respectively. With regard to the strengthening scheme, full FRCM configuration showed better performance in terms of the increase in the shear capacity and deflection at the maximum load compared to that for the intermittent counterparts.

Acknowledgments

This paper was made possible by NPRP grant # NPRP 7-1720-2-641 from the Qatar National Research Fund (a member of Qatar Foundation). The findings achieved herein are solely the responsibility of the authors.

References

Aly, R., Benmokrane, B., and Ebead, U., Tensile Lap Splicing of Bundled CFRP Reinforcing Bars in Concrete, *Journal of Composites for Construction*, 10(4), 287–294, 2006.

Ebead, U., Inexpensive Strengthening Technique for Partially Loaded Reinforced Concrete Beams : Experimental Study, *Journal of Materials in Civil Engineering*, 27(10), 2015.

Ebead, U. and Marzouk, H., Strengthening of Two-Way Slabs Using Steel Plates, *ACI Structural Journal*, 99(6), 23-31, 2002a.

Ebead, U. and Marzouk, H., Strengthening of Two-Way Slabs Subjected to Moment and Cyclic Loading, *ACI Structural Journal*, 99(4), 435–444, 2002b.

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*, 111(4), 741–751, 2014.

Ebead, U. and Saeed, H., FRP/Stirrups Interaction of Shear-Strengthened Beams, *Materials and Structures*, Springer Netherlands, 50(2), 103, 2017.

Elghazy, M., Refai, A., Ebead, U., and Nanni, A., Effect of corrosion Damage on the Flexural Performance of RC Beams Strengthened with FRCM Composites, *Composite Structures*, Elsevier Ltd, 180, 994–1006, 2017.

Elsayed, W., Ebead, U., and Neale, K., Mechanically Fastened FRP-Strengthened Two-Way Concrete Slabs with and without Cutouts, *Journal of Composites for Construction*, 13(3), 198–207, 2009.

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

Ombres, L., Structural Performances of Reinforced Concrete Beams Strengthened in Shear with a Cement Based Fiber Composite Material, *Composite Structures*, Elsevier Ltd, 122, 316–329, 2015.

Panigrahi, A. K., Biswal, K. C., and Barik, M. R., Strengthening of Shear Deficient RC T-beams with Externally Bonded GFRP Sheets, *Construction and Building Materials*, Elsevier Ltd, 57, 81–91, 2014.

Pino, V., Hadad, H., Basalo, F., Nanni, A., Ebead, U., and Refai, A., Performance of FRCM-Strengthened RC Beams Subject to Fatigue, *Journal of Bridge Engineering*, 22(10), 4017079, 2017.

Raoof, S. and Bournas, D., TRM versus FRP in Flexural Strengthening of RC Beams : Behaviour at High Temperatures, *Construction and Building Materials*, 154, 424–437, 2017.

Tetta, Z. and Bournas, D., TRM vs FRP Jacketing in Shear Strengthening of Concrete Members Subjected to High Temperatures, *Composites Part B*, Elsevier Ltd, 106, 190–205, 2016.

Tetta, Z., Koutas, L., and Bournas, D., Textile-Reinforced Mortar (TRM) versus Fiber-Reinforced Polymers (FRP) in Shear Strengthening of Concrete Beams, *Composites Part B: Engineering*, Elsevier Ltd, 77, 338–348, 2015.

Trapko, T., Urbańska, D., and Kamiński, M., Shear Strengthening of Reinforced Concrete Beams with PBO-FRCM Composites, *Composites Part B*, 80, 63–72, 2015.

Wakjira, T. and Ebead, U., Hybrid NSE/EB Technique for Shear Strengthening of Reinforced Concrete Beams Using FRCM: Experimental study, *Construction and Building Materials*, 164, 164–177, 2018.

Younis, A., Ebead, U., and Shrestha, K., Different FRCM Systems for Shear-Strengthening of Reinforced Concrete Beams, *Construction and Building Materials*, 153, 514–526, 2017a.

Younis, A., Ebead, U., and Shrestha, K. C., Tensile Characterization of Textile Reinforced Mortar, *Proceedings of the Ninth International Structural Engineering and Construction Conference, Resilient Structures and Sustainable Construction*, ISEC Press, Valencia, Spain, St-28, 2017b.

Younis, A., Ebead, U., and Shrestha, K. C., FRCM Shear Strengthening for Concrete Beams, *Proceedings of the Ninth International Structural Engineering and Construction Conference, Resilient Structures and Sustainable Construction*, ISEC Press, Valencia, Spain, St-27, 2017c.