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

AN EFFECTIVE TECHNIQUE UTILIZING FRCM SYSTEM IN STRENGTHENING RC BEAMS IN SHEAR

TADESSE WAKJIRA and USAMA EBEAD

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

This paper presents the efficacy of a new technique of fabric reinforced cementitious matrix (FRCM) for the strengthening of shear deficient reinforced concrete (RC) beams. This technique involves embedding the FRCM composites in the concrete cover and is referred to as "near surface embedded" FRCM (NSE-FRCM) technique. Five (5) medium scale rectangular RC beams of width × depth × length of 150 × 330 × 2100 mm were constructed and tested under displacement controlled with three-point loading. One beam was kept unstrengthen as a control specimen whereas the other four beams were strengthened with different types and configurations of the NSE-FRCM system. The test parameters were: (a) geometric configuration (intermittent strips of NSE-FRCM versus full NSE-FRCM plate), and (b) fabric types (carbon versus glass fabrics). The test results indicated that the NSE-FRCM technique can successfully be used to significantly enhance the shear capacity of the strengthened beams. The strengthened specimens exhibited an average enhancement in the shear capacity of 62% over the unstrengthen beam. The full NSE-FRCM plate showed higher enhancement in the shear strength compared to that for the intermittent NSE-FRCM configuration. Moreover, the specimens strengthened with carbon FRCM showed higher shear capacity compared to that with glass FRCM counterparts.

Keywords: Rehabilitation, Near surface embedded, Reinforced concrete beams, Fabric reinforced cementitious matrix, NSE-FRCM.

1 INTRODUCTION

In the construction industry, structural rehabilitation is used to restore the capacity of the deteriorated structures and increase their life span. Several structural strengthening methods and materials have been reported in the literature including ferrocement (Ebead 2015), steel plates (Ebead and Marzouk 2002), and fiber reinforced polymer (FRP) (Aly *et al.* 2006, Ebead and Saeed 2014). The latter has widely been used because of its wide range of advantages over the traditional strengthening methods that utilize steel and concrete (Kotynia *et al.* 2008). FRP composites can be applied to existing structural members in different ways; e.g. FRP wraps, externally bonded FRP (Panigrahi *et al.* 2014), mechanically fastened (Elsayed *et al.* 2009a, 2009b), hybrid mechanically fastened and externally bonded FRP (Ebead and Saeed 2014), and near surface mounted FRP (Lorenzis and Nanni 2002). However, the incompatibility of the FRP composites with the concrete substrate becomes a concern. Moreover, FRP composites have poor performance at high temperatures (Raoof and Bournas 2017). Lately, fabric reinforced cementitious matrix (FRCM) composite was introduced as a viable strengthening material that overcomes some of the problems associated with FRP composites (Shrestha *et al.* 2017, Younis *et al.* 2017b). Existing literature showed the successful application of externally bonded FRCM system for flexural and shear strengthening of RC beams (Ebead *et al.* 2017, Elghazy *et al.* 2017, Younis *et al.* 2017a, 2017c), flexural strengthening of RC slabs (Koutas and Bournas 2017), and strengthening of RC columns (Ludovico *et al.* 2010). However, the externally bonded FRCM system is characterized by debonding of FRCM composites from the concrete surface that limits the utilization of the FRCM composite to its full strength. As a remedy to this problem, the authors have recently introduced the hybrid "near surface embedded/ externally bonded" NSE/EB-FRCM technique that has the potential to reduce debonding failure mode (Wakjira and Ebead 2018). With this new technique larger number of FRCM layers can be used with less chance of debonding failure.

Thus, the paper aimed at introducing the NSE-FRCM technique for strengthening of RC beams deficient in shear. The experimental program involved construction and testing of five (5) medium scale RC beams. The test results have been discussed in terms of the shear capacity, deformational characteristics and failure modes. It has been observed that the use of the near surface embedded FRCM system (NSE-FRCM) as a stand-alone technique has the potential to mitigate FRCM/ concrete debonding.

2 EXPERIMENTAL PROGRAM

2.1 Material Properties

Ready-mixed concrete of the same batch, with an average compressive strength of 30 MPa, was used to cast the test beams. Internal reinforcement involved 16 mm diameter bars used as the main tensile reinforcement and 8 mm diameter bars used as the compressive reinforcement and ties. The longitudinal tensile reinforcement bars had an average yield strength of 595 MPa and yield strain of 2660 $\mu\varepsilon$ while the compressive and transverse reinforcement bars had an average yield strength of 535 MPa and yield strain of 2580 $\mu\varepsilon$.

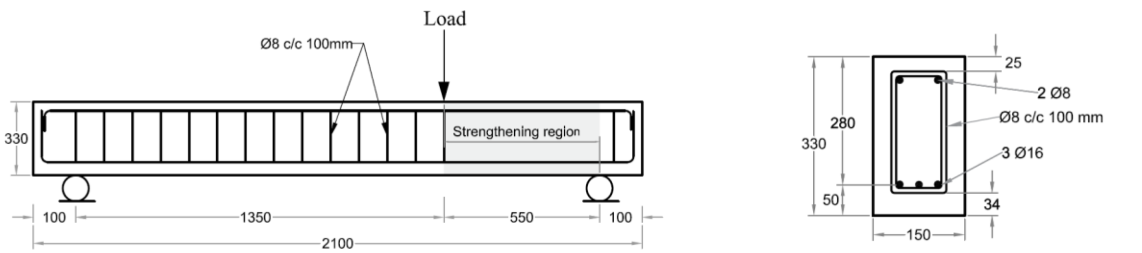
Two different types of fabrics (carbon and glass) were used along with their respective mortar types to form the two types of FRCM systems used in the NSE-FRCM strengthening system. In both fabric types, the textile roving was aligned in two orthogonal directions. For carbon fabrics, both the weft and warp roving are spaced at 10 mm and each roving has a cross-sectional area of 0.047 mm^2 in both directions. For glass fabrics, the warp and weft roving are spaced at 14 mm and 18 mm spacing, respectively. Each roving has a cross-sectional area of 0.066 mm^2 and 0.047 mm^2 in the longitudinal and transverse directions, respectively. Carbon and glass fabrics had respective tensile strength of 4.8 GPa and 2.6 GPa and elastic modulus of 240 GPa and 80 GPa. The carbon and glass fabrics had ultimate elongations of 1.8% and 3.25%, respectively.

2.2 Test Specimens and Test Matrix

The study was carried out on five (5) rectangular RC beams with 150 mm in width and 330 mm in depth. Figures 1a and 1b show the beam dimensions and reinforcement details. One beam was kept unstrengthen to act as a reference specimen whereas the other four beams were strengthened with NSE-FRCM of different geometric configuration.

Table 1 summarizes the test matrix. Two different test parameters have been investigated:

- FRCM type: two different types of FRCM composites were utilized; viz., glass (G) FRCM and carbon (C) FRCM.
- Strengthening configuration: full versus intermittent NSE-FRCM strips. The latter's configuration is 120 mm wide strips spaced at 95 mm within the critical shear span.



(a) Longitudinal detail (b) Mid-span cross-setion

Figure 1. Typical beam detail.

The NSE-FRCM technique utilized two layers of fabrics in the FRCM composite. The strengthening system involved: (a) preparation of the grooves, (b) application of first layer of the mortar followed by installation of first layer of fabrics, (c) application of second layer of mortar followed by installation of second layer of fabrics and a finishing mortar layer.

Table 1. Test matrix.

Specimen ID	**Type of fabric**	**NSE-FRCM configuration**
Control	-	-
C-Full	Carbon	Full
C-Intermittent	Carbon	Intermittent
G-Full	Glass	Full
G-Intermittent	Glass	Intermittent

2.3 Test Setup

The test was executed using Instron static universal testing machine under three-point loading. Linear variable displacement transducers were used to monitor the vertical displacement of the beam under the loading point. Moreover, concrete and steel strains were monitored using strain gauges. The steel strain gauges had 5% strain limit and 5 mm gauge length whereas the concrete strain gauge had a maximum strain limit of 0.2% and 60 mm gauge length.

3 TEST RESULTS

The test results are summarized in Table 2 in terms of the maximum load (P_u), deflection at the maximum load (Δ_u), flexural tensile strain at the maximum load (ε_u), and failure modes.

Table 2. Summary of test results.

Specimen ID	P_u **(kN)**	**Gain in** P_u **(%)**	Δ_u **(mm)**	**Gain in** Δ_u **(%)**	ε_u **(%)**	**Failure mode**
Control	104	-	3.25	-	1425	Shear
C-Full	184	77	6.48	99	2711	Shear
C-Intermittent	176	69	5.16	59	1787	Shear
G-Full	174	67	5.98	84	2426	Shear
G-Intermittent	139	34	4.53	39	1762	Shear

3.1. Shear Capacity and Failure Modes

The second and third columns of Table 2 list the load capacity and its percentage increase for the strengthened specimens relative to that of the control specimen, respectively. The NSE-FRCM strengthening system significantly increased the shear capacity of the strengthened beams with a value that ranged from 34% to 77% over the control beam. This result indicates a successful use of the NSE-FRCM system for the strengthening of shear deficient RC beams. The effectiveness of the NSE-FRCM strengthening system varied based on the test parameters.

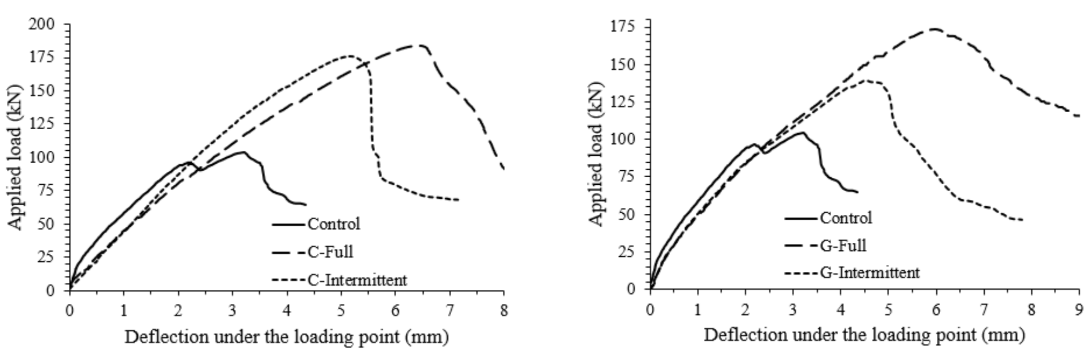
The C-FRCM system performed better than G-FRCM counterpart in enhancing the strength of the specimens. The highest gain in the shear capacity was recorded for full configuration of carbon NSE-FRCM strengthened beam. This specimen failed at an ultimate load of 184 kN that corresponds to 77% gain in the shear capacity relative to the control specimen as listed in Table 2. Glass NSE-FRCM counterpart of the same specimen failed at an ultimate load of 174 kN that corresponds to 67% gain in shear capacity as listed in Table 2.

With regard to the NSE-FRCM configuration, full configuration of NSE-FRCM showed, as intuitively expected, higher gain in the shear capacity than intermittent NSE-FRCM counterparts of Table 2. For instance, in glass FRCM specimens, the gain in the shear capacity for full NSE-FRCM plate was almost double than the shear capacity for intermittent NSE-FRCM counterpart.

All specimens exhibited a shear failure mode caused by propagation of shear cracks within the critical shear span as listed in Column 8 of Table 2. Generally, no signs of debonding of FRCM system from the substrate concrete were observed demonstrating an effective implementation of the NSE-FRCM technique for mitigating the deboning failure.

3.2. Deformational Characteristics

Figures 2a and 2b show the load versus deflection plots for carbon and glass FRCM, respectively. Moreover, the fourth and fifth columns of Table 2 list the deflection at the maximum load, Δ_u, and the percentage increase in the deflection of the strengthened specimens relative to the control beam, respectively. As can be seen in Figures 2a and 2b, the NSE-FRCM specimens showed higher deflection at the peak load compared to that for the control specimen (Δ_u= 3.25 mm). The highest gain in Δ_u was recorded for carbon FRCM specimen strengthened with full NSE-FRCM plate. Intermittent configuration of the same FRCM type exhibited 59% gain in Δ_u that was 40% lower than the value for the full configuration counterpart. Similarly, full configuration of glass NSE-FRCM plate exhibited 45% higher gain in Δ_u compared to the intermittent configuration counterpart.



(a) Carbon FRCM (b) Glass FRCM

Figure 2. Load versus deflection under the loading point for (a) carbon FRCM, and (b) G-FRCM.

As of the FRCM type, carbon FRCM specimens showed higher deflection at the peak load compared to that for glass FRCM counterparts.

With regard to the strain values, all specimens failed in shear before yielding of the longitudinal reinforcement ($\varepsilon_{t,u} < 2660\ \mu\varepsilon$) with an exception of Specimen C-Full as listed in the sixth column of Table 2. Furthermore, the NSE-FRCM technique has increased the strain in flexural reinforcement indicating that brittle shear failure has been delayed for more tensile strains in the tensile bars.

4 CONCLUSION

This paper presented a new form of FRCM strengthening system referred to as NSE-FRCM technique that has the potential to mitigate the debonding failure of FRCM off the substrate concrete. The efficacy of the NSE-FRCM system has been discussed in terms of the increase in the shear strength, deformational characteristics and failure mechanism. Generally, no debonding of FRCM system has been observed attributed to the enhanced FRCM/concrete bond. This result indicated that the NSE-FRCM technique can successfully be used to mitigate the debonding failure mode, which is the governing mode of failure in externally bonded FRCM technique. Prevention of this failure mode leads to better utilization of the FRCM composite. An overall average gain in the shear capacity of 62% has been observed. Carbon FRCM showed higher gains in the shear capacity (73% on average) compared to those of glass FRCM counterpart (51% on average). As expected, specimens strengthened with full configuration of NSE-FRCM showed higher shear capacity compared to that for the intermittent configuration counterparts indicating significance of FRCM continuity.

Acknowledgments

This paper was made possible by Qatar University grant # QUST-CENG-SPR-14/15-15 from Qatar University. 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*, (10), 2015.

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

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., Shrestha, K., Afzal, M., Refai, A., and Nanni, A., Effectiveness of Fabric-Reinforced Cementitious Matrix in Strengthening Reinforced Concrete Beams, *Journal of Composites for Construction*, 21(2), 4016084, 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., Studies on Mechanically Fastened Fiber-Reinforced Polymer Strengthening Systems, *ACI Structural Journal*, 106(1), 49–59, 2009a.

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.

Koutas, L., and Bournas, D., Flexural Strengthening of Two-Way RC Slabs with Textile-Reinforced Mortar : Experimental Investigation and Design Equations, *Journal of Composites for Construction*, 21(1), 1–11, 2017.

Lorenzis, L., and Nanni, A., Bond Between Near Surface Mounted FRP Rods and Concrete in Structural Strengthening, *ACI Structures Journal*, 99(2), 123–133, 2002.

Ludovico, M., Prota, A., and Manfredi, G., Structural Upgrade Using Basalt Fibers for Concrete Confinement, *Journal of Composites for ConstructionConstruction*, 14(5), 541–552, 2010.

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.

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

Shrestha, K. C., Ebead, U., and Younis, A., Effect of Surface Roughening on Concrete/TRM Bond, *Proceedings of the Ninth International Structural Engineering and Construction Conference, Resilient Structures and Sustainable Construction*, ISEC Press, Valencia, Spain, St--43, 2017.

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.