FRCM/stirrups interaction in RC beams strengthened in shear using NSE-FRCM

U Ebead and T G Wakjira

Department of Civil and Architectural Engineering, Qatar University, Doha, Qatar
uebead@qu.edu.qa

Abstract. The use of a recently introduced "near surface embedded" (NSE) technique for fabric reinforced cementitious matrix (FRCM) system is shown to be a viable alternative to the conventionally used externally bonded FRCM counterpart with the potential to mitigate FRCM/concrete debonding. This paper presents a study on the interaction of FRCM and stirrups for RC beams strengthened in shear using the NSE-FRCM system. The experimental program involved eight (8) rectangular RC beams with and without internal shear reinforcement. Two test variables were considered; namely, fabric type (carbon, glass and polyparaphenylene benzobisoxazole) and internal shear reinforcement within the critical shear span (with and without stirrups). The experimental results revealed that the NSE-FRCM can successfully be used to enhance the shear capacity of the strengthened beams. Carbon FRCM was the most effective of all the fabric types. Moreover, an interaction between the stirrups and the NSE-FRCM system has been observed. The percentage gain in the shear strength was reduced from 69% to 38% due to the presence of stirrups within the critical shear span. Moreover, the NSE-FRCM strengthening has reduced the strain in the stirrups owing to the load sharing between the stirrups and the strengthening system.

1. Introduction and background

The light weight and corrosion resistant fiber reinforced polymer (FRP) has been used extensively as a structural strengthening system [1–6]. However, FRPs are characterized by poor performance at extreme weather conditions and poor compatibility with the concrete substrate[7]. The development of fabric reinforced cementitious matrix (FRCM) has shown to overcome these problems. Fabric reinforced cementitious matrix (FRCM) system has found to be promising for the strengthening of deteriorated reinforced concrete (RC) beams [8–14]. Shear strengthening performance of FRCM system depends on various factors including FRCM type [15,16], number of fabric layers [17], geometric configuration [18,19], presence of end anchorage [20], and strengthening orientation [21]. In addition to these, the amount of internal shear reinforcement greatly influences the strengthening efficacy of the FRCM system. However, literature available on the effect of varying internal shear reinforcement on the efficacy of FRCM system are scarce [22,23]. Furthermore, the available literature focused on the use of a single type of externally bonded (EB)-FRCM system; carbon FRCM [22,23].

Gonzalez-Libreros et al. [22] studied the behaviour of shear deficient RC beams strengthened with carbon EB-FRCM system. The strengthening system reduced the strain in the stirrups. On the other hand, an increase in the amount of internal shear reinforcement reduced the strain in the FRCM composites. Similar results were reported by Oluwafunmilayo et al. [23] studying the efficacy of carbon FRCM in strengthening of shear deficient RC beams with varying internal shear reinforcement (without stirrups, 6 mm diameter stirrups spaced at 75 mm and 150 mm). The failure in all strengthened beams was governed by FRCM debonding off the concrete. This type of failure is typical failure mode in externally bonded FRCM system limiting the full utilization of the material [24]. The hybrid "near surface embedded/externally bonded" NSE/EB-FRCM technique recently introduced by the authors has shown to mitigate the debonding failure mode [25].

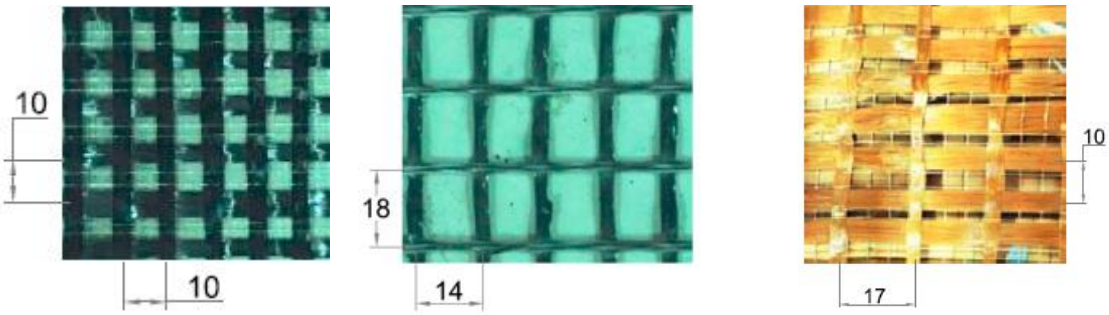
In light of the aforementioned gaps, the present study investigates the interaction of stirrups and FRCM system in the strengthening of shear deficient RC beams. For this purpose, experimental tests have been carried out on eight (8) medium scale RC beams with and without internal shear reinforcement. Three different types of FRCM composites were used; viz., carbon, PBO and glass.

2. Experimental program

2.1. Material

All beams were casted using ready-mixed concrete of the same batch. The mean 28-day compressive strength of concrete was 30 MPa based on the tested samples. The flexural reinforcement involved 16 mm diameter tensile reinforcement bars and 8 mm diameter compressive reinforcement bars. The transverse reinforcement involved 6 mm diameter bars within the CSS (for specimens with stirrups) and 8 mm bars outside the CSS. The flexural and transverse reinforcement had an average yield strength of 535 MPa and 595 MPa, respectively.

Three different types of fabrics were used in the FRCM composites; namely, carbon, glass, and PBO fabrics as shown in Figures 1a through 1c, respectively. The geometric and average mechanical properties of the fabrics were provided in Table 1.The fabrics were used along with the manufacturer recommended mortar types [26–28]. Two layers of fabrics were utilized in the FRCM strengthening system.



(a) (b) (c)

Figure 1. Types of fabrics (a) carbon fabric, (b) glass fabric, and (c) PBO fabric.

Table 1. Geometric and average mechanical properties of the fabrics.

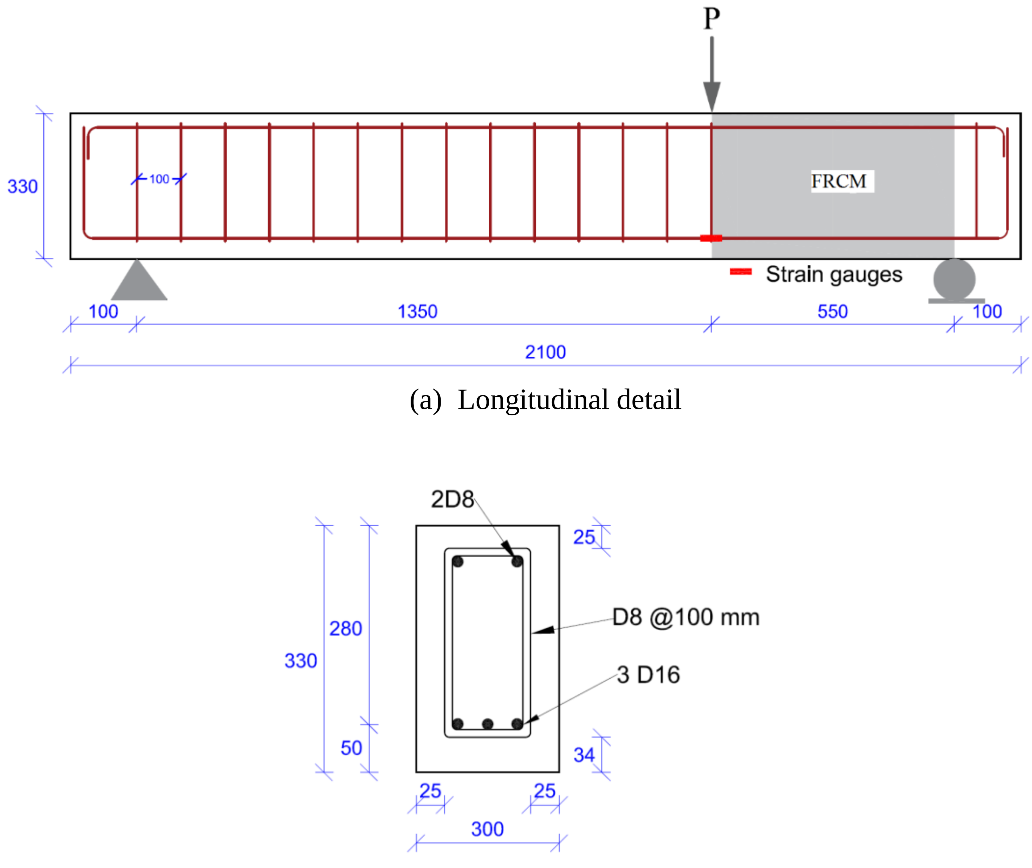
Fabric type	Area per width in the warp direction (mm^2/mm)	Area per width in the weft direction (mm^2/mm)	Modulus of elasticity (MPa)	Tensile stress (MPa)	Ultimate strain (με)
Glass	0.047	0.066	80000	2600	32500
Carbon	0.047	0.047	240000	4800	18000
PBO	0.045	0.0155	270000	5800	21500

2.2. Test beams

Figures 2a and 2b show the longitudinal and cross-sectional details of the beam specimens, respectively. The test specimens comprised eight (8) full-size rectangular RC beams (150 mm in width, 330 mm in depth, and 2100 mm in length). The beams had a total span between supports and a shear span of 1900 mm and 550 mm as shown in Figure 2a. The specimens were grouped into two sets with four number of beams in each set. Each set includes one reference specimen (without strengthening) and three strengthened specimens. The first set has no internal shear reinforcement

IOP Conf. Series: Materials Science and Engineering **431** (2018) 112001 doi:10.1088/1757-899X/431/11/112001

within the CSS while the second set was reinforced with 6 mm diameter stirrups spaced at 215 mm within the CSS (internal transverse reinforcement ratio, $\rho_{str} = 0.0018$). Three bars of 16 mm diameter were used as flexural reinforcement and two bars of 8 mm diameter were used as compression reinforcement.
The beam designation used in this study followed two key parameters; namely, fabric type and amount of internal shear reinforcement within the CSS. The first letter denotes the fabric type (C- for carbon, G- for glass and P- for PBO) whereas the second number represents the amount of transverse reinforcement (0 – meaning no stirrups within the CSS and 1 meaning there are stirrups) as listed in Table 2.



(b) Cross-sectional detail at the mid-span

Figure 2. Beam detail (all dimensions are in mm).

2.3. Test setup
The beams were tested under three-point loading as simply supported system. Two linear variable displacement transducers (LVDT) were used to measure the vertical displacement under the loading point. The strains in the tensile bars were monitored with two steel strain gauges attached to the tensile reinforcement bars directly under the load location. Three more steel strain gauges were used to monitor the strains in the stirrups for the specimens reinforced with stirrups within the CSS. The concrete strain gauge was used to monitor the strains in the compression concrete just below the loading point.

3. Results and discussion
Table 2 summarizes the experimental test results in terms of the maximum load capacity (P_{max}), the gain in P_{max}, deflection at the maximum load (δ_{max}) and strain values.

Table 2. Test results.

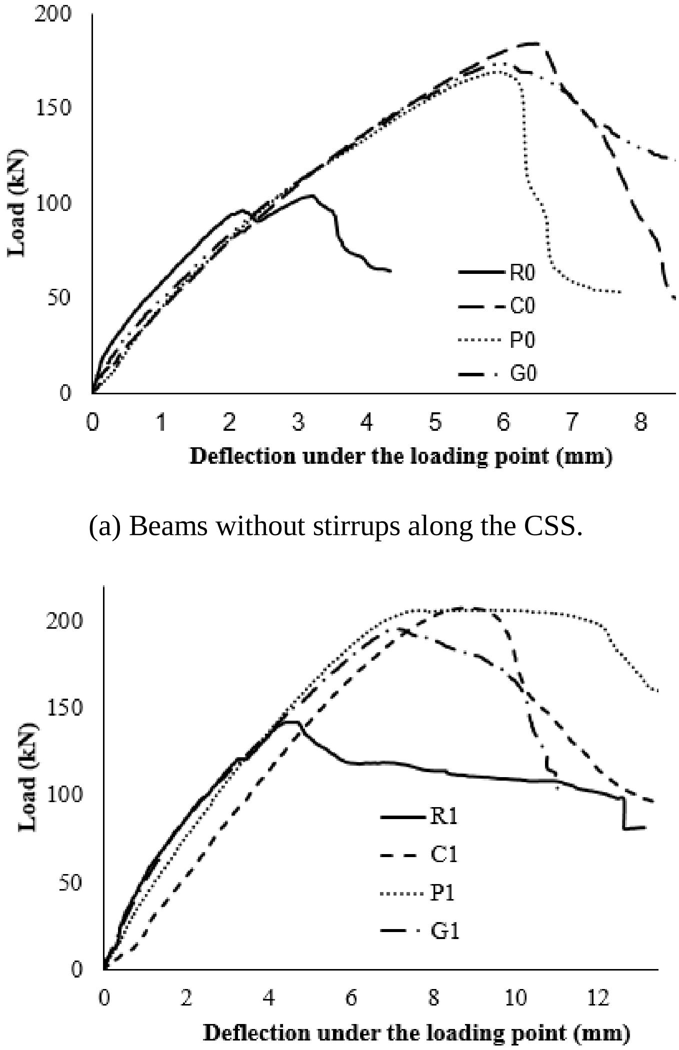
Specimen ID	ρ_{str}	Fabric type	P_{max} (kN)	Percentage gain in P_{max} (%)	δ_{max} (mm)	$\varepsilon_{s,u}$ (με)	$\varepsilon_{c,u}$ (με)
R0 (reference)	-	-	104	-	3.3	1425	-
C0	-	Carbon	184	77	6.5	2711	2036
P0	-	PBO	169	63	5.9	2457	1153
G0	-	Glass	174	67	6.0	2426	1891
R1 (reference)	0.0018	-	142	-	4.7	2000	467
C1	0.0018	Carbon	208	46	8.7	5699	1914
P1	0.0018	PBO	183	29	9.0	2121	2121
G1	0.0018	Glass	196	38	7.1	-	1768

3.1 Load Carrying Capacity

The strengthening system showed significant increase in P_{max} with an average gain that ranged between 29% and 77% relative to the associated reference specimens as listed in Table 2. The effectiveness of the FRCM system is dependent on whether or not there are stirrups within the CSS. The reference specimen for the beams without stirrups within the CSS (R0) failed at a load of 104 kN while that for R1 was 142 kN. Therefore, the experimental value for the contribution of the stirrups resisting shear is 38 kN. The average enhancement in P_{max} for specimens without stirrups was 69%. This ratio was reduced to 38% for the specimens with stirrups. These results indicate that the contribution of FRCM system is reduced due to an existence of stirrups; which is consistent with previous findings for externally bonded FRCM system [22,23] and FRP [29]. As of the FRCM type, C-FRCM strengthened specimens performed better than PBO- and G-FRCM counterparts. For example, the specimen with stirrups along the CSS and strengthened with full configuration of C-FRCM system, C1, showed 46% enhancement in P_{max}. This gain in P_{max} was reduced to 45% and 38% for PBO-FRCM and G-FRCM counterparts; namely, P1 and G1, respectively as listed in Table 2.

3.2 Deformational Characteristics

Figures 3a and 3b show the load versus deflection plots. Moreover, the deflection at the maximum load (δ_{max}) is listed in Column 6 of Table 2. As can be seen from these figures and Table 2, the strengthened specimens experienced higher δ_{max} compared to that for their respective reference specimen. For the specimens without stirrups within the CSS, δ_{max} ranged from 5.9 mm to 6.5 mm compared with a deflection of 3.25 mm for the reference specimen (R0) as listed in Table 2. This represents an increase in δ_{max} ranging from 81% to 100%. On the other hand, δ_{max} for the specimens reinforced with stirrups within the CSS ranged from 7.1 mm to 9.0 mm compared with a deflection of 4.7 mm for their benchmark (R1) representing an increase in δ_{max} ranging from 51% to 91% as listed in Table 2. These results showed that the strengthening system has significantly increased the deflection of the strengthened beams, which may be considered as improvement in the ductility behavior of the strengthened specimens.



(a) Beams without stirrups along the CSS.

(b) Beams reinforced with stirrups within the CSS.

Figure 3. Applied load versus deflection under the loading point.

The strain developed in the tensile bar ($\varepsilon_{s,u}$) and compressive strain in concrete ($\varepsilon_{c,u}$) are listed in the last two columns of Table 2. As can be seen from this table, the flexural steel strains in the longitudinal bars were generally below the yield strain (2660 μƐ) with an exception of carbon FRCM specimens. Moreover, the compressive strains in the concrete were less than the concrete crushing strain (3500 μƐ) suggesting that shear failure took place. The strengthening system has significantly enhanced the strains developed in the longitudinal bar. For the specimens without stirrups within the CSS, $\varepsilon_{s,u}$ ranged from 2426 μƐ to 2711 μƐ compared with a strain of 1425 μƐ for the reference specimen (R0) as listed in Table 2. The steel strains for the strengthened specimens with stirrups within the CSS ranged from 2121 μƐ to 5699 μƐ compared with a strain value of 2000 μƐ for the reference specimen (R1) as listed in Table 2. This observation indicates that the strengthening system has delayed the brittle type of shear failure.

With the regard to the strains in the stirrups within the CSS, the strengthened specimens exhibited lower strain values compared to that for the reference specimen due to "load sharing" between the stirrups and the FRCM strengthening system. For instance, the strain developed in the reference specimen (R1) at the peak load (142 kN) was 2499 μƐ. At the same load of 142 kN, Specimen C1 exhibited 238 μƐ in the stirrups

4. Conclusion

This paper presents an experimental study on the efficacy of the NSE-FRCM system and its interaction with the internal shear reinforcement. The experimental program involved eight medium-scale RC beams deficient in shear with two test variables studied: (a) FRCM types and (b) presence of internal shear reinforcement (with and without stirrups within shear span). The main findings from the experimental results are summarized as follows.

- FRCM strengthening system using NSE technique significantly enhanced the maximum load capacity of the strengthened specimens relative to the reference (unstrengthen) specimens. The gain in P_{max} ranged from 29% to 77% relative to the benchmarks. The performance of the FRCM system was reduced with an existence of stirrups within the CSS. The average gain in the maximum load capacity due to the FRCM strengthening system was reduced from a value of 69% recorded for the specimens without stirrups within the CSS to 38% for the specimens with stirrups.
- With regard to the type of the composite, C-FRCM strengthening system performed better than PBO- and G-FRCM system.
- The strengthening system enhanced the deformational characteristics of the strengthened specimens relative to the benchmark. The average increase in the deflection at the ultimate load was 89% and 76% for the specimens without and with stirrups within the CSS, respectively.
- The interaction between the FRCM system and internal shear reinforcement has been observed. The FRCM strengthening system reduced the strain in the stirrups relative to the reference specimen.

5. References

[1] Dias SJE, Barros JAO 2010 Performance of reinforced concrete T beams strengthened in shear with NSM CFRP laminates. *Eng Struct* 32:373–84. doi:10.1016/j.engstruct.2009.10.001.
[2] Rocca S, Galati N, Nanni A. 2006 Large-size reinforced concrete columns strengthened with carbon FRP: experimental evaluation. *Proc, 3rd Inter Conf FRP Compos Civ Eng* 1–4.
[3] Ebead U, Marzouk H. 2004 Fiber-reinforced polymer strengthening of two-way slabs. *ACI Struct J* 101:650–9. doi:10.14359/13387.
[4] Aly R, Benmokrane B, Ebead U. 2006 Tensile Lap Splicing of Bundled CFRP Reinforcing Bars in Concrete. *J Compos Constr* 10:287–94. doi:10.1061/(ASCE)1090-0268(2006)10:4(287).
[5] Elsayed W, Ebead U, Neale K. 2009 Studies on mechanically fastened fiber-reinforced polymer strengthening systems. *ACI Struct J* 106:49–59.
[6] Ebead U. 2012 Hybrid Externally Bonded / Mechanically Fastened Fiber-Reinforced Polymer for RC Beam Strengthening. *ACI Struct J* 108:669–78.
[7] Ebead U, Saeed H. 2013 Hybrid shear strengthening system for reinforced concrete beams : An experimental study. *Eng Struct* 49:421–33. doi:10.1016/j.engstruct.2012.11.039.
[8] Ebead U, Shrestha K, Afzal M, Refai A, Nanni A. 2017 Effectiveness of fabric-reinforced cementitious matrix in strengthening reinforced concrete beams. *J Compos Constr* 21:4016084. doi:10.1061/(ASCE)CC.1943-5614.0000741.
[9] Pino V, Hadad H, Basalo F, Nanni A, Ebead U, Refai A. 2017 Performance of FRCM-strengthened RC beams subject to fatigue. *J Bridg Eng* 22:4017079. doi:10.1061/(ASCE)BE.1943-5592.0001107.
[10] Elghazy M, Refai A, Ebead U, Nanni A. 2017 Effect of corrosion damage on the flexural performance of RC beams strengthened with FRCM composites. *Compos Struct* 180:994–1006. doi:10.1016/j.compstruct.2017.08.069.
[11] Younis A, Ebead U, Shrestha KC. 2017 FRCM Shear Strengthening for Concrete Beams. Proc. Ninth Int. Struct. Eng. Constr. Conf. Resilient Struct. Sustain. Constr., Valencia, Spain: ISEC Press; p. St--27.

[12] Elghazy M, El Refai A, Ebead U, Nanni A. 2018 Post-repair flexural performance of corrosion-damaged beams rehabilitated with fabric-reinforced cementitious matrix (FRCM). Constr Build Mater 166:732–44. doi:10.1016/j.conbuildmat.2018.01.128.
[13] Raoof S, Koutas L, Bournas D. 2017 Textile-reinforced mortar (TRM) versus fibre-reinforced polymers (FRP) in flexural strengthening of RC beams. *Constr Build Mater* 151:279–91. doi:10.1016/j.conbuildmat.2017.05.023.
[14] Oluwafunmilayo A, El-Maaddawy T, Ismail N. 2017 Fabric-reinforced cementitious matrix: A promising strengthening technique for concrete structures. *Constr Build Mater* 132:94–111. doi:10.1016/j.conbuildmat.2016.11.125.
[15] Azam R, Soudki K. 2014 FRCM strengthening of shear-critical RC beams. *J Compos Constr* 18:1–9. doi:10.1061/(ASCE)CC.1943-5614.0000464.
[16] Escrig C, Gil L, Bernat-Maso E, Puigvert F. 2015 Experimental and analytical study of reinforced concrete beams shear strengthened with different types of textile-reinforced mortar. *Constr Build Mater* 83:248–60. doi:10.1016/j.conbuildmat.2015.03.013.
[17] Triantafillou T, Papanicolaou C. 2006 Shear strengthening of reinforced concrete members with textile reinforced mortar (TRM) jackets. *Mater Struct* 39:93–103. doi:10.1617/s11527-005-9034-3.
[18] Contamine R, Si Larbi A, Hamelin P. 2013 Identifying the contributing mechanisms of textile reinforced concrete (TRC) in the case of shear repairing damaged and reinforced concrete beams. *Eng Struct* 46:447–58. doi:10.1016/j.engstruct.2012.07.024.
[19] Ombres L. 2015 Structural performances of reinforced concrete beams strengthened in shear with a cement based fiber composite material. *Compos Struct* 122:316–29. doi:10.1016/j.compstruct.2014.11.059.
[20] Brückner A, Ortlepp R, Curbach M. 2008 Anchoring of shear strengthening for T-beams made of textile reinforced concrete (TRC). *Mater Struct* 41:407–18. doi:10.1617/s11527-007-9254-9.
[21] Al-Salloum Y, Elsanadedy H, Alsayed S, Iqbal RA. 2012 Experimental and numerical study for the shear strengthening of reinforced concrete beams using textile-reinforced mortar. *J Compos Constr* 16:74–90. doi:10.1061/(ASCE)CC.1943-5614.0000239.
[22] Gonzalez-Libreros JH, Sneed L, D'Antino T, Pellegrino C. 2017 Behavior of RC beams strengthened in shear with FRP and FRCM composites. *Eng Struct* 150:830–42. doi:10.1016/j.engstruct.2017.07.084.
[23] Oluwafunmilayo A, E l-Maaddawy T, Refai A. 2015 Numerical simulation and experimental testing of concrete beams strengthened in shear with fabric-reinforced cementitious matrix. *J Compos Constr* 20:1–11. doi:10.1061/(ASCE)CC.1943-5614.0000711.
[24] Younis A, Ebead U, Shrestha K. 2017 Different FRCM systems for shear-strengthening of reinforced concrete beams. *Constr Build Mater* 153:514–26. doi:10.1016/j.conbuildmat.2017.07.132.
[25] Wakjira T, Ebead U. 2018 Hybrid NSE/EB technique for shear strengthening of reinforced concrete beams using FRCM: Experimental study. *Constr Build Mater* 164:164–77. doi:10.1016/j.conbuildmat.2017.12.224.
[26] Ruredil, Technical datasheet. Ruredil X Mesh Gold n.d.
[27] SIKA Technical datasheet. SikaWrap-350G Grid data sheet, 2016. n.d.
[28] Ruredil, Technical datasheet. X MESH C10 RUREDIL X MESH C10 2013:1–6.
[29] Ebead U, Saeed H. 2017 FRP/stirrups interaction of shear-strengthened beams. *Mater Struct* 50:103. doi:10.1617/s11527-016-0973-7.

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.