Behaviour of RC beams strengthened in shear using near surface embedded FRCM

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Abstract. This paper presents an experimental study on the efficacy of a lately introduced "near surface embedded" technique (NSE) for fabric reinforced cementitious matrix (FRCM) for the strengthening of reinforced concrete (RC) beams in shear; considering two test variables: (a) fabric type (glass and carbon) and (b) strengthening configuration (intermittent versus full). For this purpose, five (5) simply supported medium-scale RC rectangular beams have been tested under displacement controlled monotonic three-point loading. The experimental results showed that the FRCM system is effective in strengthening of shear deficient RC beams. An average of 62% gain in the shear capacity has been achieved due to the FRCM strengthening system. Carbon FRCM owning the higher axial rigidity showed better performance than that of glass FRCM. The average gain in the shear capacity for carbon FRCM strengthened beams was 22.5% higher than that for glass FRCM strengthened beams. Moreover, full strengthening configuration showed better performance than that for the intermittent configuration counterparts confirming the significance of the FRCM continuity and its quantity in enhancing the shear capacity of the strengthened beams.

1. Introduction and background

The demand for rehabilitation of structure through effective strengthening methods has been increased due to deterioration of the structural members caused by different factors, e.g., corrosion of reinforcement bars, inadequate maintenance, overloading and environmental factors including seismic events and hurricane. Scholars have suggested different strengthening methods including steel plates [1], ferrocement [2], and fiber reinforced polymer (FRP) [3]. Different techniques have been used to optimize the use of the FRP strengthening system including externally bonded (EB) FRP [4–6], near surface mounted (NSM) [7], mechanically fastened (MF) [8,9], and hybrid externally bonded and mechanically fastened FRP [4,12]. However, FRP possess some drawbacks such as incompatibility with the substrate concrete and failure at extreme weather conditions. The development of fabric reinforced cementitious matrix has shown to be a viable alternative to the FRP counterparts that circumvent the problems in FRPs [13]. It possess good resistance to high temperatures and is compatible with the substrate concrete unlike FRPs [14–16]. FRCM is composed of a cement-based matrix reinforced with high strength textile fabrics. The latter is used to carry tensile stresses while the mortar acts as a binding agent and to transfer the stresses between the substrate and the fabrics.

Existing literature revealed successful usage of FRCM system for strengthening of RC beams in shear and flexure [17–20] and flexural strengthening of RC slab [21] when externally applied to the surface of the structural members (s). However, externally bonded FRCM system is associated with debonding of the FRCM off the substrate concrete [4,18,22,23]. On the other hand, the hybrid near surface embedded/externally bonded FRCM (NSE/EB-FRCM) system was shown to be effective in reducing and or preventing this type of failure and thus increase the utilization of the strengthening material [24]. With this technique, it was possible to use thicker or larger number of FRCM layers (i.e. 4 layers) with low or no tendency of debonding.

This paper presents the use of near surface embedded FRCM system in which the FRCM is embedded in the prepared groove. A total of five medium-scale RC beams have been fabricated and tested with two test variables considered: (a) FRCM type and (b) strengthening configuration.

2. Experimental program

2.1. Test beams

The experimental program comprised of five medium-scale rectangular RC beams constructed and tested as simply supported system under three-point bending. The beams had a cross-sectional dimension of 150 mm × 330 mm (width × depth) and a clear span of 1,900 mm between the supports. The reinforcement in the beams involved 16 mm diameter bars used as main flexural reinforcement and 8 mm bars used as compression reinforcement and ties. All beams were unreinforced in shear within the test region and thus are critical in shear. Outside the test region the beams were reinforced in shear with 8 mm bars spaced at 100 mm.

Two test parameters were considered; viz., FRCM type and its geometric configuration. In the FRCM composite, two different types of fabrics were used; namely, carbon and glass fabrics. Moreover, the strengthening was done in two different configurations; i.e., continuous FRCM plate (Figure 1a) and intermittent FRCM strips (Figure 1b). The intermittent configuration used three strips of 150 mm wide with 95 mm spacing within the test region as shown in Figure 1a.

(a) Full FRCM configuration

(b) Intermittent FRCM configuration
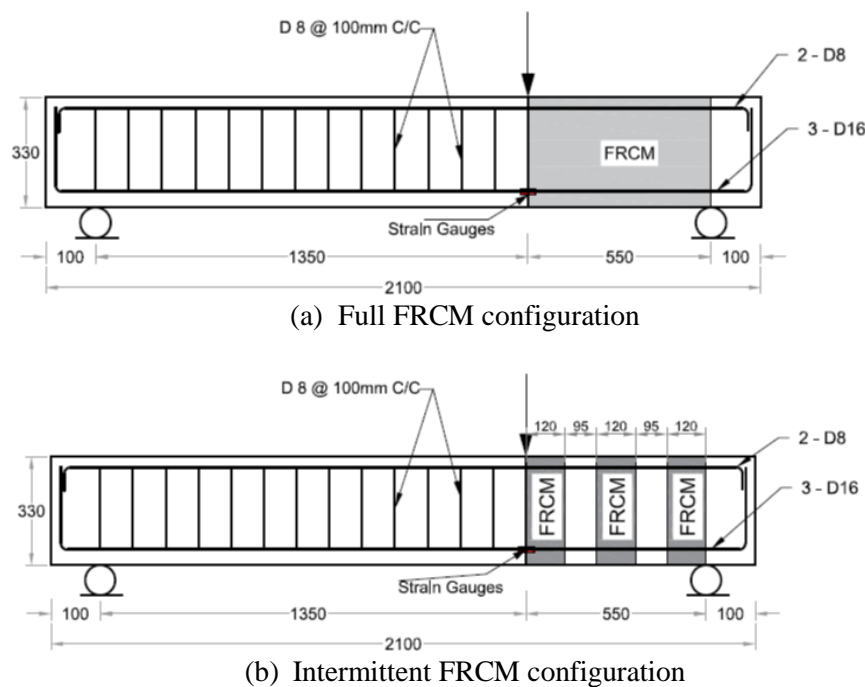
Figure 1. Longitudinal detail of strengthened beam.

2.2. Materials and strengthening procedure

Casting of the beams was done using ready-mixed concrete of the same batch. The average compressive strength of the concrete was 30 MPa based on the test result of standard cylindrical concrete samples. The reinforcement bars used 8 mm and 16 mm diameter bars. The 8 mm diameter bar had a yield strength of 535 MPa, a yield strain of 0.258%, an ultimate deformation of 12.47%, and an elastic modulus of 207 GPa. The 16 mm diameter bars had a yield strength of 595 MPa, a yield strain of 0.266%, an ultimate deformation of 9.12%, and an elastic modulus of 224 GPa.

Two different types of textile fabrics were used in the FRCM composite along with their associated mortar, provided by the manufacturer [25–27]. Table 1 provides the average mechanical and geometric properties of the fabrics including the fabric thickness in the direction of the warp ($t_{f,warp}$),

fabric thickness in the direction of the weft ($t_{f,weft}$), modulus of elasticity (E_f), tensile strength (f_f), ultimate deformation ($\varepsilon_{u,f}$), and compressive strength of the associated mortar ($f_{c,m}$).

Table 1. Fabric properties.

Fabric type	$t_{f,warp}$ (mm)	$t_{f,weft}$ (mm)	E_f (GPa)	f_f (GPa)	$\varepsilon_{u,f}$ (%)	$f_{c,m}$ (MPa)
Carbon (C)	0.0047	0.0047	240	4.8	1.8	20
Glass (G)	0.0047	0.066	80	2.6	3.25	40

The producer recommended that mortar mix for carbon FRCM and PBO-FRCM use 7 litres of water for every 25 kg of mortar and 5 litres of water for every 25 kg of mortar for glass FRCM. The strengthening system used two (2) layers of fabrics in the FRCM composite. Specimen preparation and strengthening procedures are summarized below.

- Preparation of grooves: Grooves of 15 mm depth was made on both sides of the beams using the slitting tool. The prepared groove provided roughened concrete surface with minimal or no need for further roughening. The dry concrete surface was then cleaned and dampened with water to a saturated surface dry (SSD) condition.
- Application of the FRCM system: A thin first layer of mortar was applied followed by installation of a first layer of fabrics. A second layer of mortar followed by installation of a second layer of fabrics and a finishing mortar layer completed the strengthening process.

2.3. Test setup and procedure

The beam specimens were tested under monotonic three-point bending test as a simply supported system as shown in Figure 2. The load was applied using an Instron Universal Testing Machine under displacement controlled loading at a rate of 0.25 mm/mm. Two linear variable displacement transducers, one on each side of the beam, were placed under the loading point to measure the displacement under the load at each load step as shown in Figure 2. Moreover, concrete and steel strain gauges were used to monitor the strains in the concrete and tensile reinforcement bars. All data were recorded using a data acquisition system.
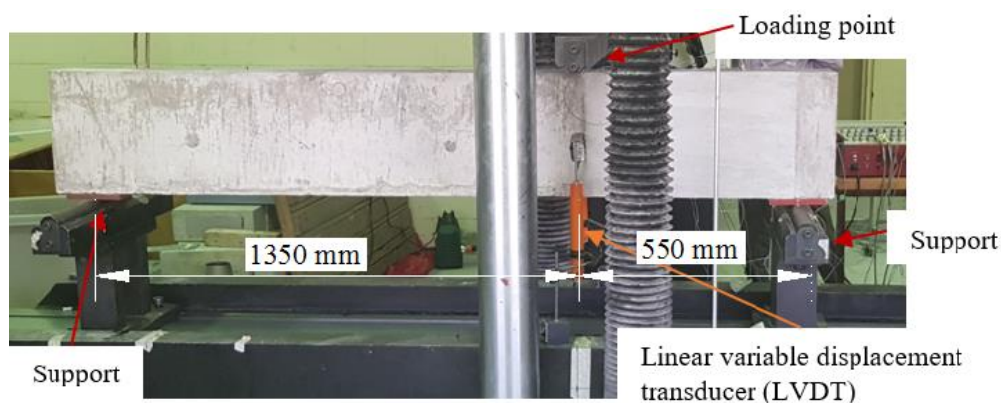
Figure 2. Test setup

3. Results and discussion

The test results are given in Table 2 and discussed in terms of the peak load (P_{max}), percentage enhancement in the load carrying capacity relative to the reference specimen, deflection at the peak load (δ_{max}), compressive strains measured in the concrete at the peak load ($\varepsilon_{c,max}$), tensile strains measured in the flexural bars ($\varepsilon_{s,max}$) at the peak load, and energy absorption (ψ).

**Table 2.** Test results.

Beam	Fabric type	FRCM configuration	P_{max} (kN)	Gain in P_{max} (%)	δ_{max} (mm)	$\varepsilon_{s,max}$ (%)	ψ (kN.mm)
Ref	-	-	104	-	3.25	0.1425	238
C-F	Carbon	Full/continuous	184	77	6.48	0.2711	753
C-I	Carbon	Intermittent	176	69	5.16	0.1787	571
G-F	Glass	Full/continuous	174	67	5.98	0.2426	694
G-I	Glass	Intermittent	139	34	4.53	0.1762	387

3.1. Ultimate strength

The FRCM strengthening has significantly increased the load carrying capacity of the strengthened beams. The average increase in the load carrying capacity relative to the reference specimen (Ref = 104 kN) was 73% for carbon FRCM strengthened beams and 50.5% for glass FRCM strengthened beams. This result demonstrates that the FRCM strengthening system can be used to significantly enhance the shear capacity of the strengthened beams.

Figure 3a and 3b show the effect of the test variables on the performance of the strengthening system in enhancing the load capacity of the strengthened beams.

(a)   (b)
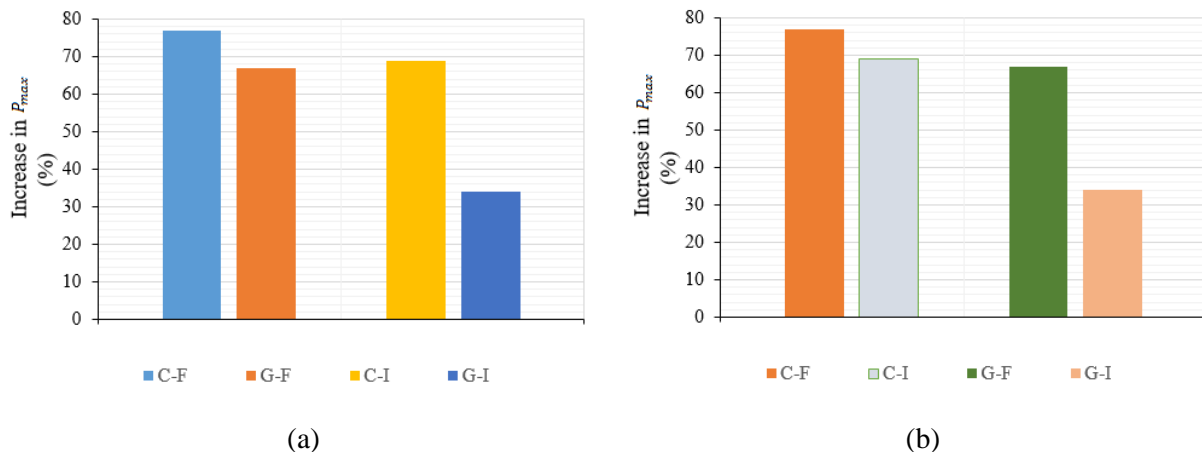
Figure 3. The effect of (a) FRCM type and (b) FRCM configuration on the percentage gain in the ultimate load (P_{max}).

As can be seen in Figure 3a and Table 2, carbon FRCM performed better than glass FRCM in terms of the gain in the load carrying capacity due to the higher axial rigidity (EA) in the former. For instance, Specimen C-F sustained an ultimate load of 184 kN corresponding to 77% gain in the ultimate load. On the other hand, the glass FRCM counterpart of the same specimen; i.e., G-F showed a lower gain in the ultimate load of 67% as shown in Figure 3a and Table 2. Similarly, Specimen C-I (69%), strengthened with intermittent C-FRCM strips, showed more than double the gain in the ultimate load of that for Specimen G-I (34%).

Figure 3b shows the effect of FRCM geometric configuration on the percentage gain in the load carrying capacity due to the strengthening system. As can be seen in this figure and Table 2,

continuous FRCM configuration showed higher increment in the ultimate load compared to that for the intermittent FRCM strips confirming the significance of FRCM continuity and quantity.

3.2. Deformational characteristics

Figures 4 shows the load-displacement curves for the tested beams. As can be seen in this figure, all strengthened beams exhibited significantly higher displacement at the peak load (δ_{max}) compared to that for the reference beam. Specimen C-F, strengthened with full configuration of carbon FRCM, showed the highest value for δ_{max} of 6.48 mm which was almost double the value for the reference specimen as shown in Figure 4 and Table 2. Its intermittent configuration counterpart, C-I, showed δ_{max} value of 5.16 mm which was lower than the value for Specimen C-F. Similarly, Specimen G-F (5.98 mm) showed higher δ_{max} than that for its intermittent configuration counterpart, G-I (4.53 mm). Thus, the continuity of the FRCM system was effective in enhancing the deformation behaviour of the strengthened beam. Moreover, carbon FRCM was more effective in increasing the displacement of the beams at the peak load as shown in Figure 4. For instance, the δ_{max} value for Specimen C-I (5.16 mm) was higher than that for the Specimen G-I (4.53 mm) as shown in Figure 4 and Table 2.

Column 7 of Table 3 lists the values of the flexural strains in the tensile reinforcement bars. As can be seen in this table, the strengthened beams failed before yielding of the flexural bars with an exception of Specimen C-F that failed just after yielding point. This result suggests that the beams failed in shear. Moreover, the strengthened beams exhibited higher strain in the flexural bars compared to that for the reference specimen indicating that the strengthening system was effective in delaying the brittle type shear failure.
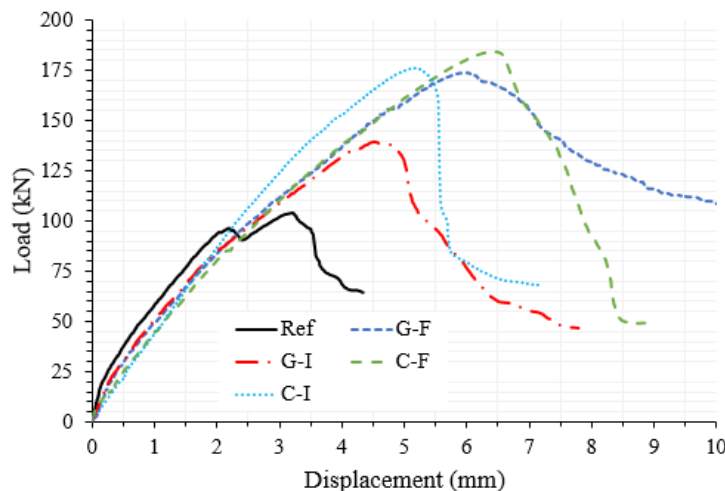
Figure 4. Load versus displacement curves.

The last column of Table 3 lists the energy absorption (ψ) values, which is defined as the area under the load versus displacement plots up to the peak load [11,12,28]. The reference specimen exhibited an energy absorption value of 238 kN.mm while all the strengthened beams showed significantly higher values of ψ relative to the reference beam. The average enhancement in the absorption energy was 153% due to the FRCM strengthening system.

As of the FRCM type, specimens strengthened with carbon FRCM showed higher absorption energy that that for the glass FRCM counterparts. Moreover, the full FRCM plate was effective in increasing the energy absorption values.

4. Conclusion

This paper presents the behaviour of RC beams strengthened in shear using a new form of near surface embedded FRCM system for strengthening of RC beams. Two different types of FRCM composites were used; i.e., carbon and glass FRCM. Moreover, the strengthening system used both continuous/full and intermittent FRCM strips. Thus, two different test parameters have been studied:

(a) FRCM type and (b) strengthening configuration. For this purpose, a total of five medium-scale RC beams have been fabricated and tested under monotonic displacement controlled three-point loading. One beam was unstrengthened to act as a control while the remaining four beams were strengthened in shear. The test results showed that the FRCM strengthening system can successfully be used to enhance the load carrying capacity and deformation characteristics of RC beams. The following conclusions have been drawn from the experimental test results.

- An average of 62% gain in the ultimate load relative to the reference beam has been observed due to the FRCM strengthening system.
- Carbon FRCM performed better than glass FRCM counterpart due to its higher axial stiffness. For instance, the percentage gain in the ultimate load was higher for Specimens C-F (77%) and C-I (69%) than that for their corresponding glass FRCM beams; namely, G-F (67%) and G-I (34%), respectively.
- The continuity of the FRCM system was effective in enhancing the ultimate load of the strengthened beam. In both carbon and glass FRCM, the full strengthening configuration performed better than its intermittent configuration counterparts.
- The FRCM strengthening system also significantly increased the deflection of the strengthened beams relative to that of the unstrengthen reference beam. The average gain in the deflection was 79% for carbon FRCM beams and 62% for glass FRCM beams.
- The energy absorption of the strengthened beams has been significantly enhanced due to the FRCM strengthening system. The percentage gain in the absorption energy was 178% for carbon FRCM beams and 127% for glass FRCM beams relative to the reference beam.

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