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FLEXURAL STRENGTHENING OF RC BEAMS USING GLASS-FRCM

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ABSTRACT

Externally bonded Fiber reinforced polymer (FRP) sheets made of fiber net embedded in epoxy matrix has been successfully used in the repair and strengthening of both the shear and flexural capacities of reinforced concrete (RC) beams, slabs and columns since the 90's. Although the epoxy gives the system most of its durability, it is also responsible for many disadvantages, such as poor performance in elevated temperature and fire, lack of permeability, as it traps moisture, and degradation when exposed to ultraviolet radiation. In order to avoid such drawbacks, composite material utilizing cement-based matrix called Fabric Reinforced Cementitious Matrix (FRCM) has been recently introduced. The FRCM system consists of fiber-reinforced composites in the form of meshes or grid embedded in a cementitious bonding material. This research investigated the flexure strengthening of reinforced concrete (RC) beams with glass-FRCM. The experimental study included characterization of the mechanical properties of GFRCM through axial tensile testing on 20 coupon specimens. Also, four large scale, 150 mm x 250 mm x 2400 mm, reinforced internally with steel bars had been constructed, strengthened in flexure with FRCM and tested under four-point bending. The investigated parameters included the internal steel reinforcement ratio. Test results showed that GFRCM did not affect the ultimate load capacity of the beams, however, the ultimate midspan deflection was increased. Debonding/Delamination of the FRCM was observed. Continuation of this research is going on, on which U-wrapped strips will be used to ensure no debonding of the FRCM from concrete substrate.

Keywords: Strengthening, Fabric/textile Reinforcement, Cement matrix Composite Section, GFRP, FRCM.

1. INTRODUCTION

Structural rehabilitation is considered one of the most important aspects of the construction industry. Deterioration of concrete structures is a very common problem that is faced by Civil Engineers all over the world. Deterioration results in an unsafe, and weak structures. Deteriorated structures may be demolished in case of sever damage, however in many cases and under moderate damage, rehabilitation can be a very economic solution. The rehabilitation of damaged, corroded and deteriorated existing structures is one of the most critical issues facing Civil Engineers. There are generally three terms used to represent rehabilitation, these terms are repairing, retrofitting, and strengthening. Repairing is generally used when a structure is damaged, cracked, or deteriorated. Repairing helps in restoring the structural performance of the structure. Whereas, strengthening is a term used when improving the existing structural performance of a structure. Strengthening acts as a great alternative for traditional structural repairing because when strengthening the structure is also repaired. Strengthening is usually done to structural members such as beams, columns, and slabs. Retrofitting can be defined as the modification or upgrading of the structure to make it withstand design changes done to its original requirement. Seismic retrofitting is a very common rehabilitation done to structures to improve its resistance to seismic activity. Common rehabilitation techniques such as section enlargement, crack repairs, external posttensioning, external bonded FRP sheets, and steel plate bonding.

Externally bonded Fiber reinforced polymer (FRP) sheets made of fiber net embedded in epoxy matrix has been successfully used in the repair and strengthening of both the shear and flexural capacities of reinforced concrete (RC) beams, slabs and columns since the 90's (Mahoney, 2013). Today, fiber-reinforced composites are widely used as strengthening system of existing reinforced concrete structures. FRP systems are made of composite fibers embedded in an epoxy adhesive. The epoxy gives the system some of its properties in terms of bonding and resistance to environment. The epoxy is also responsible of many disadvantages for engineers and builders, such as its lack of permeability, as it traps moisture, thereby threatening bonding integrity of RC (D'Ambrisi and Focacci, 2011), in addition to its poor performance in elevated or low temperature conditions (Tumialan and De Luca, Structure Mag.). Not to mention FRP's sensitivity to ultraviolet radiation when exposed to light, and its high toxicity (Turk, 2013). Also, the epoxy is considered a toxic hazard to the installer. Due to the mentioned drawbacks of FRP, its use is limited. In order to avoid such drawbacks, cement based composites systems are used. These cement-based composites were later called FRCM (Fiber Reinforced Cementitious Matrix). Therefore, with the advancement of science and breakthroughs in nanotechnology, fiber reinforced cementitious matrix (FRCM) has become a very popular solution proposed to overcome those disadvantages. The FRCM system consists of fiber-reinforced composites in the form of meshes or grid embedded in a cementitious bonding material. There are many other common terms used in the literature to describe FRCM such as TRM (textile reinforced mortar) and TRC (textile reinforced concrete). TRC and TRM are terms commonly used in Europe. FRCM, unlike FRP, is less affected by temperature fluctuations and possesses porous properties that allow moisture to diffuse through RC structures where FRCM is applied (Tumialan and De Luca, Structure Mag.). In comparison to FRP, FRCM is inherently incombustible (D'Ambrisi and Focacci, 2011), hence, making it a much safer and more convenient alternative to commonly used FRP. In addition, research has shown that FRCM can be applied to concrete structures and columns in low temperature conditions and onto wet surfaces, not to mention its ability to act as a strengthening material to resist seismic loading (D'Ambrisi and Focacci, 2011)

2. PREVIOUS RESEARCH

In the last decade a lot of researches were conducted to correctly evaluate the tensile performance of FRCM composites. A very important and comprehensive research was performed by Arboleda et al (2015) to study the characterization of the tensile behaviour of FRCM composites. The characterization was done under two different boundary conditions, clevis and clamping grips. Five different FRCM systems were used. To characterize the tensile behavior of the FRCM system, rectangular coupons having dimensions of 410x50x10 mm were manufactured and tested.

The first boundary condition was a clevis grip assembly. This gripping criterion consisted of two steel plates glued to the ends of the coupons. The steel plates had a thickness of about 3mm and a bond length of about 150mm. The steel plates were pinned to a transversal pin on the extended part of the plates, and this whole system was connected to a clevis joint, which was pinned to a shackle. The other test set-up consisted of a clamping grip. This gripping criteria was obtained by gluing GFRP tabs at the ends of the coupons, and then fixing (clamping) the two ends to the testing machine. The two different test set-ups were tested having an extensometer of 100 mm gauge length positioned at the middle of the coupon.

It was noticed that using the clamping grip, the coupons was allowed to reach it ultimate strength by limiting slippage failure. When clevis grip is used the failure mode is dominated by the slipping of the fabrics from the mortar. The clevis grip presents a more realistic failure that will be expected in the field. It can be concluded from this test, that the objective of the test will dictate what type of gripping system to be used. If the purpose of the characterization test is to find the ultimate tensile strength of the system, then, clamping grip should be used. And, if the purpose of the test is to determine the design parameters of the system, then, a clevis grip should be used.

Previously, many researches were performed to evaluate the performance of the FRCM systems on various applications. Ombres (2011) studied the performance of reinforced concrete beams strengthened with PBO-FRCM. Two main parameters were considered: a) number of layers b) Strengthening scheme (continuous and discontinuous wrapping). It was noticed that an increase of 25% in the ultimate load capacity in comparison with the control beam strengthened with continuous U-wrapped PBO-FRCM. Due to the use of the U-wrapped PBO-FRCM, the failure mode was flexure and ductile failure, in comparison with the control beam, which observed a diagonal shear crack followed by brittle failure. When using discontinuous U-wrapping scheme (located at the same position of the steel stirrups), the performance is not as good and a shear failure happened. Also, It was noticed that the additional number of layers did not have a positive effect to the load resistance due to an inadequate width/spacing ratio of the strips. The inadequate width/spacing ratio does not permit the activation or contribution of some of the wrapping strips.

D'Ambrisi (2011) investigated the effectiveness of FRCM (fiber-reinforced cementitious matrix) for the flexural strengthening of RC beams experimentally. Two main FRCM materials are tested, Carbon fiber nets and PBO (poliparafenilenbenzobisoxazole) fiber nets. Three main parameters were inspected: 1) Net shapes, 2) Different matrices (bonding mortar material) 3) Number of layers. Experimental results of the tests performed showed clearly that FRCM materials are very effective for strengthening RC beams in flexure. Also, results showed that beams strengthened with PBO-FRCM materials performed better than C-FRCM materials. It was concluded that the debonding and detaching characteristics of FRCM and Concrete are depending mainly on the number of fiber nets and fiber arrangements (D'Ambrisi, Feo, Focacci, 2012). Also, the fiber nets shapes are very important in determining the effectiveness of the system as in this test two different carbon fiber nets were used.

Babaeidarabad et al (2013) performed an experimental study to investigate the effectiveness of PBO-FRCM to externally strengthen RC beams in flexure. Test parameters for this experiment are number layers (one and four layers) and compressive strength of concrete (low-29.1 MPa and high-42.9 MPa). Each test was replicated three times. The FRCM system was bonded on the bottom (tension) side. Experimental results show that FRCM improved the flexural capacity of RC beams. It was noticed that all the control beams failed by crushing of concrete. The increase in strength for low-strength concrete is higher than that of high-strength concrete. For low-strength concrete, flexural capacity increased 32% (1-layer) and 92% (4-layers). For high-strength concrete, flexural capacity increased by 13%(1-layer) and 73% (4-layers).

Loreto et al (2013) studied the performance of RC-Slab-Type element externally bonded with PBO-FRCM. The experimental test took two parameters into account: a) Concrete Strength b) Number of layers (one and four). Two concrete strengths were considered, low (29.13 MPa) and high (42.91 MPa). Steel reinforcement ratio was selected in a manner to ensure an under-reinforced behaviour. The authors found that the performance of PBO-FRCM demonstrates a very promising composite material for strengthening of Slab-Type RC. It worked greatly as a strength enhancer as the strength for the beams tested increased in a range of 135% and 212%. The observed failure modes were the typical expected failures of FRCM, which are the slippage of the fabric within the matrix and delamination of the FRCM from the concrete substrate (D'Ambrisi 2011). Crushing of concrete followed those failures.

Azam et al (2014) investigated the effectiveness of different types of FRCM composite systems in strengthening shear critical RC beams. Two main parameters were inspected: 1) Strengthening material (G-FRCM or C-FRCM) 2) Strengthening scheme (side bonded or u-wrapped). In general, it was noticed that the FRCM shear strengthening significantly increased the ultimate load-carrying capacity of the shear-critical RC beams. The increase in ultimate load ranged between 19% and 105% when using strengthening material. Also, there was a substantial increase in the deflection at ultimate, ranging between 10% and 220%. It was noticed that the strengthening scheme affected GFRCM more than its effect on CFRCM. For U-wrapped configuration, the beam tends to resist higher load compared to side-bonded configuration due to the confinement effect of the U-wrapping.

In comparison with the control beam, the beams strengthened with one layer FRCM had a similar crack pattern to that of the control beam, and due to this crack pattern, the crack developed into the FRCM, which made the slippage of the fabric visible. Whereas, for the beams strengthened with four layer FRCM, the FRCM system helped in reducing the crack's width, and in which the cracks were not developed into FRCM exposed surface. This caused the FRCM to delaminate rather than slippage. Neither case did the FRCM reach its ultimate tensile strength and failed in rupture. It was noticed that in terms of ductility, the FRCM decreased the ductility of the RC Beam in both cases due to the mentioned nature of the failures that played an important role in decreasing the ultimate deflection at mid-span.

As mentioned and discussed above, many researches studied the flexural behaviour of beams strengthened with FRCM. However, the previous researches focused on the PBO and Carbon-FRCM as a flexural strengthening systems and not glass-FRCM. This research focuses on comparing the efficiency of using glass-FRCM in the flexure strengthening of reinforced concrete (RC) beams with glass-FRCM compared to PBO and C-FRCM. The tested parameter of this phase was the steel reinforcement ratio. The experimental study included characterization of the mechanical properties of GFRCM through axial tensile testing on 20 coupon specimens. Also, four large scale, 150 mm x 250 mm x 2400 mm, reinforced internally with steel bars had been constructed, strengthened in flexure with FRCM and tested under four-point bending.

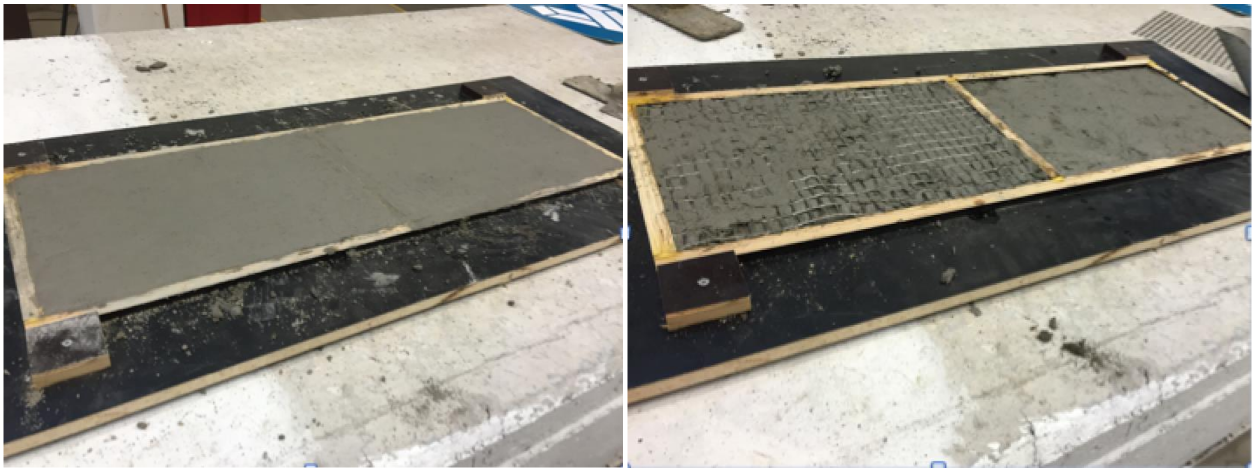
3. EXPERIMENTAL PROGRAM

The experimental program consists of two main phases. The first phase includes the characterization of the mechanical properties of the glass-FRCM through tensile testing. The second phase consists of testing four large-scale RC beams, two of which were strengthened with G-FRCM systems.

3.1 Tensile Characterization of G-FRCM

3.1.1 Coupons specimen preparation

Two sets of specimens were prepared. The first set consists of one-layered specimens and the other set consists of two-layered specimens. Coupons having dimensions of 410*50*15 mm were prepared from the FRCM panels as shown in figure 1. The mortar or the cementitious matrix was mixed according to the specifications provided by the manufacturer in which 3.5L to 3.78L of water was used per 22.7 Kg mortar. The mixing was done using a heavy duty, low-speed drill with Propeller-type paddle. The panels were prepared first by laying mortar of 5 mm nominal thickness, then putting the fabric grid, and then covering that fabric grid with another 5 mm of mortar. Same procedure applies for the second layer of grid



(a) Plan view of test specimen (b) Test specimen during construction

Figure 1: Details of test specimen for Series I

Moist curing was maintained for the first 24 hours as per the ACI 308R-01 recommendations for concrete curing. Panels were then left to cure for 28 days. After 28 days, the panels were cut using wet diamond saw. It was very important to use a wet-diamond saw to prevent any cracking or damage to the coupons. After cutting, the coupons were left to dry.

3.1.2 Materials Properties

The specimens were fabricated using Sika Wrap-350 Glass Grid and Sika Monotop 623 Mortar. The Glass net used in this study is a balanced bi-directional glass fabric net having an alkali resistant coating. The mortar used is a one-component, polymer-modified and early strength gaining, cementitious mortar. As provided by the manufacturer, the density of the mortar is 2030 kg/m3 (126 lb/ft3) as per ASTM C185. The mortar has a compressive strength of 18 MPa (after 24 hours), 30 MPa (after 7 days) and 40 MPa (after 28 days) as per ASTM C109. Table 1 lists the mechanical properties of the glass fabrics.

Table 1: Mechanical properties of the Glass-Fabric (as provided by the manufacturer)

Characteristics	Unit	Dry Fiber Properties
Tensile Strength	MPa(N/mm^2)	2600
Tensile Modulus of Elasticity	GPa	80
Fiber Density	g/cm^3	2.6
Weight per Area	g/m^2	295

3.1.3 Test Set-up and Instrumentations

Four Steel tabs with clevis openings were glued covering 100 mm on each end on both sides upper and bottom as shown in figure 2(c). Uniaxial tensile testing was carried out for the coupons gripped with a clevis grip to allow the slippage of fabrics to control the failure. The coupons were tested according to Annex A of AC434 (ICC Evaluation Service 2013). Initially, the test was performed using steel tabs glued to the ends and were clamped. Clip-on extensometer was installed to measure the strain. The clip-on extensometer covered 50 mm of the coupon and was positioned at the middle of the coupon. After testing few coupons, it was realized that the position of the initial crack does not occur at the middle due to the stresses caused by the clamping force at the ends of the coupon as shown in figure 2(a). The gripping mechanism was changed and clevis grips were used instead. The clevis grip consists of two shackles connected to each other and pinned to the steel tabs on the specimen and the testing fixture. Also, two 50 mm clip-on extensometer covering the top and bottom end of the exposed surface was used. Since, the clip-on extensometer cannot cover the whole exposed surface of the coupon, it was then replaced with the MTS Video Extensometer. To use the video extensometer, special preparation procedures should be followed. Spectral paint should be applied to the specimen surface to allow point-to-point strain measurement.

(a) Initial test setup with clamping grips

(b) Initial clevis test set-up with two clip-on extensometer

(c) Coupons after gluing steel

Figure 2: Test Preparation

The video extensometer was used tracking four target points, two of them were located within the two ends of the exposed coupon, and the other two were located at the top and bottom steel plates. The load was applied under displacement control. A loading rate of 0.2mm/min was applied.

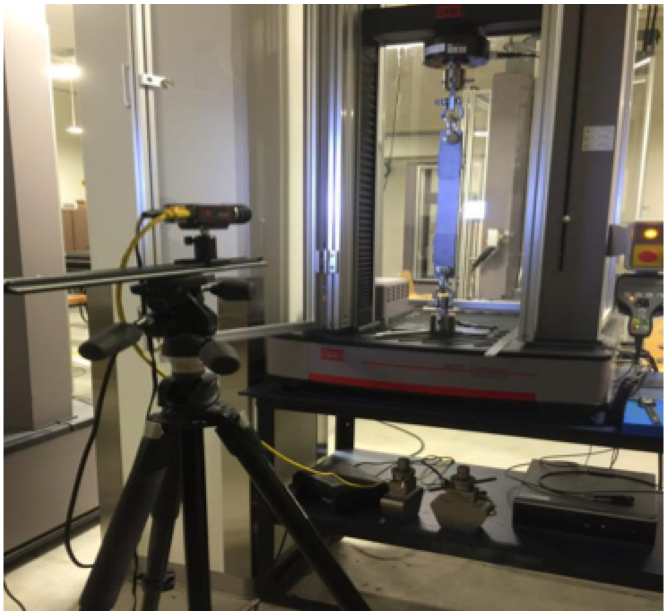


Figure 3: Final Test set-up

3.1.4 Test Results and Discussion:

As per the AC434, at least five coupons were tested and data were recorded. One and two layered coupons were tested. The expected stress-strain behaviour of FRCM under uniaxial tensile was observed. The first phase represents the linear uncracked state of the FRCM and this is observed in the first linear stage of the stress-strain curve in figure 4. Then, as the load increases, the stress transfers from the mortar to the fabric that is represented by the multicracking process of the matrix as shown in figure 4. The point or stage at which the first crack takes place is called transition point and also called bend-over point (Mobasher 2012). The transition point represents the beginning of the multicracking process. The transition point is not visible in all FRCM systems and depends mainly on the elastic modulus of the fabric.

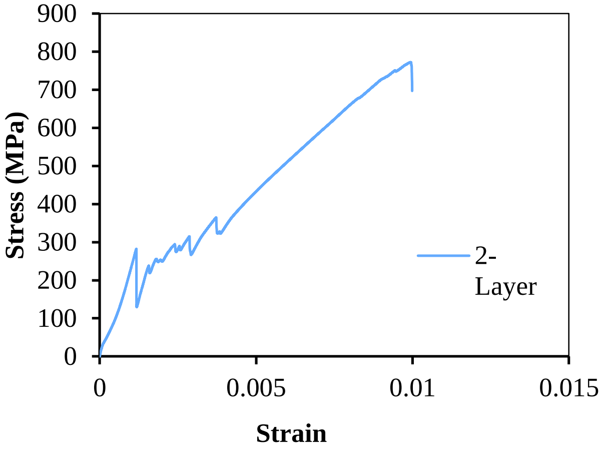


Figure 4: Stress-strain curve for G-FRCM.

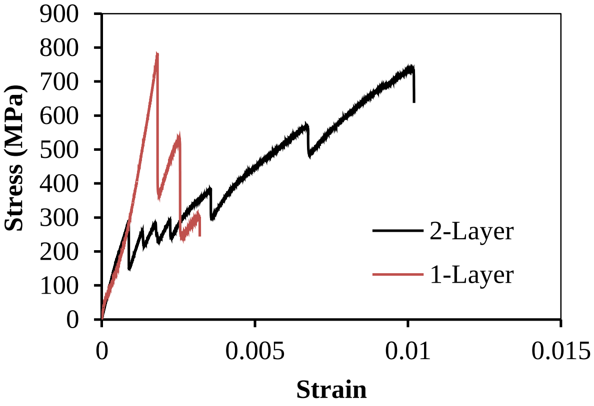


Figure 5: Two Layer versus one-layer stress-strain behaviour

The G-FRCM coupons tested showed a trilinear behaviour except in one-layered coupons on which this behaviour was not visible. On those 1-layered coupons, the multicracking phase was also not visible because of the low elastic modulus of the glass fiber, and also mainly due to the variation in thickness in comparison with the two-layers coupons as shown in figure 5. It was noticed that the ultimate tensile stress obtained by the two-layered is consistent with the one-layered. Both sets of specimens failed mainly due to slippage of glass fibers, except in few of the two-layered coupons, where the ultimate capacity of the fabric was reached and the rupture of fibers was observed.

In order to characterize the tensile performance of the FRCM systems, the following characteristic parameters were calculated based on the net fabric area:

- Ultimate tensile strain, ε_{fu}
- Ulimate tensile stress, f_{fu}
- Modulus of Elasticity of the cracked specimen E_f

The variation in the uncracked tensile strength was much higher than that of the cracked strength, and this is mainly due to the location of the first crack. When the first crack happens close to the boundary ends, the system seems to have a much lower uncracked tensile modulus. The stress is computed by dividing the load induced by the cross-sectional area of the fabric as provided by the manufacturer. The modulus of elasticity of the cracked specimen is computed using the equation provided by the AC434 below. This equation takes cracked elastic modulus as 90% of the stress subtracted by 60% of the stress divided by the subtraction of both strains for both stress respectively. AC434 equation to compute the modulus of elasticity of the cracked specimen:

$$E_f = \frac{\Delta f}{\Delta \varepsilon} = \frac{0.9 f_{fu} - 0.6 f_{fu}}{\varepsilon_{@0.9 f_{fu}} - \varepsilon_{@0.6 f_{fu}}}$$

Table 2: Mechanical Properties of Glass-FRCM Coupons tested according to AC434

FRCM Property	Symbol	Mean	Standard Deviation	COV (%)
Modulus of Elasticity of the cracked specimen	E_f	59.8 (GPa)	7.8 (GPa)	13
Ultimate tensile strength	f_{fu}	715 (MPa)	41 (MPa)	5.7
Ultimate tensile strain	ε_{fu}	0.00935 (mm/mm)	0.000632 (mm/mm)	6.7
Fiber Area per unit width[1]	A_f	0.0473 mm^2		

[1] This value is provided by the manufacturer

3.2 Beam Testing

3.2.1 Test Program

A total of four beams were tested: two control beams and two strengthened beams. The parameter investigated is the steel reinforcement ratio. Two steel reinforcement ratios were used, 1.26% (4#10M) and 1.91%(3#15M), which corresponds to $0.42\rho_b$ and $0.63\rho_b$. Two layers of G-FRCM were used on the strengthened beams.

3.2.2 Specimen Preparation

The specimens were casted and left to cure for more than 28 days. The average compressive strength was measured by testing three cylinders with a nominal diameter of 101.6 mm (4 in) for each beam. In order to apply the FRCM, the beam's surface was roughed using a hammer and chisel. Then, the surface was dampened with clean water, but without having any standing water at the surface. The Glass mesh was held in place in the bottom of the beam by gluing few points to the surface. Then, the mortar was applied, followed by a layer of the mesh. This procedure was repeated for the additional layers. Proper curing procedure was then followed.

3.2.3 Test Set-up

A four bending test was carried out on a simply supported beams with a span of 2200mm. Hydraulic actuator was used to apply the load. A spreader beam was used to spread the load to get a four-point bending moment criteria. Two Linear Variable Differential Transducers (LVDTs) were used to measure the deflection on the beam at the midspan and at location of load. Another LVDT was used to measure the crack width of the critical crack located around the midspan. Two strain gauges were used to measure the strain at the steel reinforcement. Four bi-gauges were used to measure the strain of the beam. First two were located at the top and bottom surfaces of the beam at midspan. The other two were located at the top and bottom surfaces of the beam at about one third of the span (around the contact location of the load).

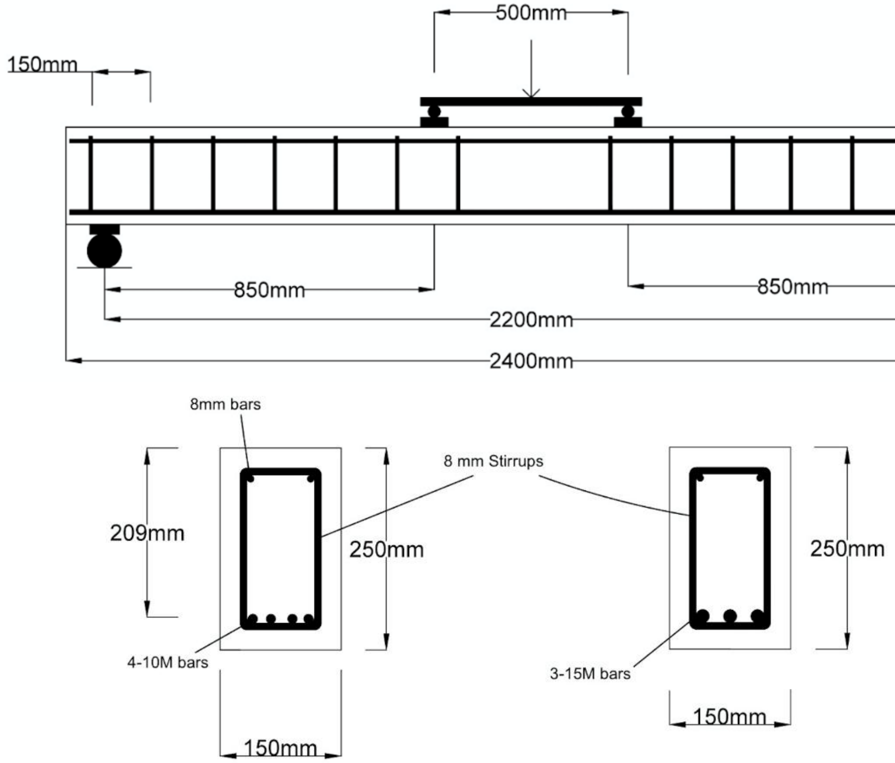


Figure 6: Beam specimen set-up and reinforcement details

3.2.4 Results and Discussion

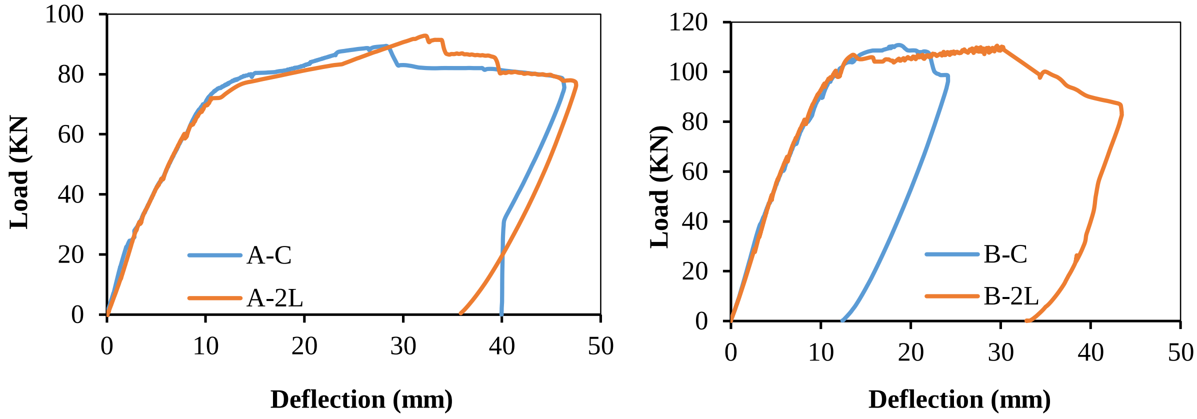
Test results are summarized in table 3. In general, it was observed that the G-FRCM system used did not impact the ultimate strength capacity as the increase. However, the system enhanced the ductility of the beam, in which the maximum deflection at the midspan was 48.5mm and 43.5mm, compared with a deflection of 46.3mm and 24.1 mm for the control beams. This represents a maximum increase of 80.5% in maximum deflection at the midspan. All the beams failed as expected by concrete compression failure. The beams repaired/strengthened failed in a manner in which the FRCM system debonded/delaminated followed by concrete compression as shown in figure 8. The debonding started at the critical moment region, and propagated in both directions, causing a loss in strengthening action by the G-FRCM. Figure 7 presents the load-deflection relationship for the four beams tested. Each graph displays two curves to compare the control vs. FRCM strengthened beam. Almost identical load-deflection patterns were noticed for the control and strengthened beam. From the diagrams, it can be observed that the FRCM increased the ultimate deflection capacity of the beam. With the given results, the delamination limited the strengthening contribution of the FRCM, and therefore, the next phase of the beam testing will include U-wrapping strips at different locations of the beam to ensure perfect debonding between the FRCM and the concrete substrate. Also, to prevent any delamination that might occur.

Table 3: Summary of Test Results

Beam[1]	f'c (MPa)	ρ	Ultimate Load (KN)	Maximum deflection @ midspan (mm)	Crack width (mm)	Failure mode
A-C	31	$0.42\rho_b$	89.3	46.3	3.7	C
A-2L	31	$0.42\rho_b$	92.82	48.5	2.4	DB-C
B-C	31	$0.63\rho_b$	110.8	24.1	2.9	C
B-2L	31	$0.63\rho_b$	110.5	43.5	0.9	DB-C

Note: Failure mode is designated by C, which indicates concrete compression failure, and DB-C indicates debonding or delamination of the FRCM system followed by concrete compression failure.

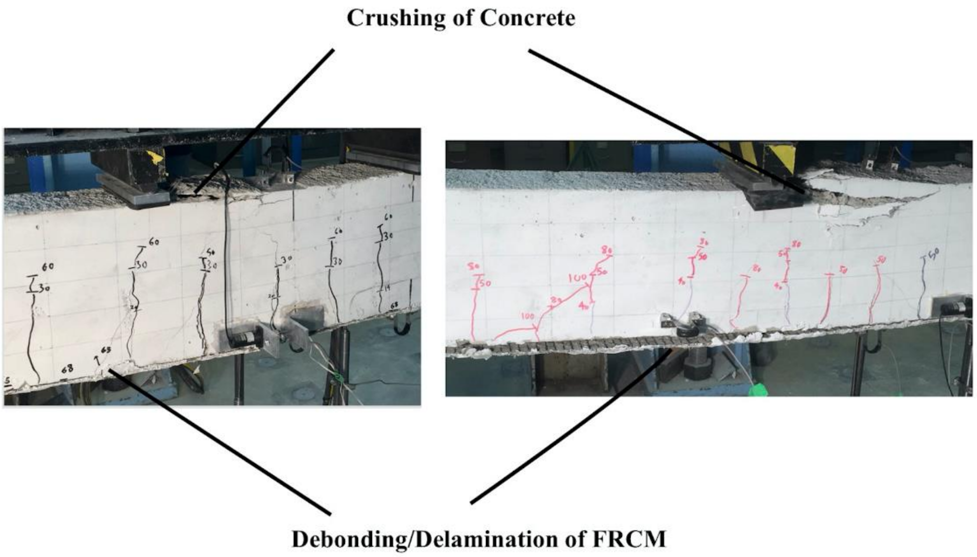
[1] Beam designation – A indicates steel reinforcement of 4#10M



(a) A-beams (4#10M)

(b) B-beams (3#15M)

Figure 7: Load-Deflection diagrams


Crushing of Concrete

Debonding/Delamination of FRCM

Figure 8: Failure modes of strengthened beams

4. CONCLUSION

In this research, characterization of the mechanical properties of G-FRCM was performed as per the AC434 code through axial testing of 20 coupons. Different gripping systems and instrumentation procedures were inspected and results were discussed. Initially, clamping gripping mechanism was used, but then was changed to clevis grip to provide less compressive stress at the boundaries of the specimen and also to allow slippage between the fibers and the cementitious matrix. Also, initially, clip-on extensometer was used, but then was switched to video extensometer due to limited capability of the clip-on extensometer on which only 50 mm of the specimen can be covered. One and two FRCM-layers configurations were tested. It was noticed that on the two-layered specimen the typical trilinear behaviour of FRCM coupons was clearly visible, whereas on the one-layered specimens, the behaviour was more of a bilinear one. The ultimate tensile stress of both configurations was consistent.

Four large-scale RC beams were constructed and tested. Two beams were strengthened in flexure with two layers of G-FRCM. Generally, it was observed that the G-FRCM did not affect the ultimate capacity of the beams. This is mainly due to the debonding/delamination of the FRCM from the beam. However, the ductility was improved, in which a maximum increase of 80.5% of the maximum deflection at midspan. The next phase of this research will include testing beams having U-wrapped FRCM strips at different locations of the beam to prevent delamination of the FRCM system. This is expected to improve the strengthening performance of the FRCM in comparison with beams tested in the current phase of the test.

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