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A NOVEL AND EFFECTIVE ANCHORAGE SYSTEM FOR ENHANCING THE FLEXURAL CAPACITY OF RC BEAMS STRENGTHENED WITH FRCM COMPOSITES

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ABSTRACT

Previous experimental studies revealed that anchorage systems were able to increase the efficiency of fiber reinforced polymers (FRP) in terms of the flexure or shear enhancements and ductility performance of the structural members. This study was conducted to investigate the suitability and effectiveness of two anchorage systems for enhancing the bond performance of fiber reinforced cementitious matrix composite (FRCM), a more recent strengthening technique using a cementitious-based binding system. In the interest of improving its flexural performance, two anchorage systems were examined here: a glass spike anchor and a novel U-wrapped anchor. The novel U-wrapped anchor is a PBO strip where its' ends had only the fabrics in the longitudinal direction that gathered and anchored into the concrete using epoxy adhesive agent. The idea behind anchoring the ends of the U-wrapped PBO strip into RC beams was to rely on the high tensile strength of the PBO strip to control the premature debonding of the

FRCM composite. Real-scale simply supported RC beams were examined under the effect of strengthening with different reinforcement ratios and with and without anchorage systems engagement. Test results revealed the contribution of anchorage systems in preventing or delaying the FRCM debonding failure mechanism and enhancing the flexural performance of strengthened beams.

Keywords: Anchorage; U-wrapped PBO anchorage; glass spike; FRCM strengthening; flexural behavior.

1. Introduction and Background

Different types of anchorage systems have been used to delay the premature debonding failure mode associated with FRP composites. The successful anchorage systems have allowed the FRP's composite materials to continuously carry a load in shear or flexure in which extra benefits from high-strength fabrics were achieved. Thus, proper anchorage systems can reduce the required cross-sectional area of the expensive fabric materials or provide a better structural performance with respect to increasing in the fabrics reinforcement ratio. Some of the important anchor types are mechanical anchorages, U-wrapped sheets, anchor spikes, and FRP rods. Many experimental studies have illustrated the efficiency and applicability of these anchorage systems. Khalifa et al. [1] invented a novel anchor that was used to reduce the stress concentration of FRP systems at the ends. The novel anchor consisted of FRP sheets that were extended through a groove filled with epoxy that may or may not include an FRP rebar. Khalifa et al. [1] stated that "the u-anchor system provides an effective solution for cases in which the bonded length of FRP composites is not sufficient to develop its full capacity.'' Wu and Huang [2] and You et al. [3] used mechanical anchorages with FRP composites. The authors concluded that the mechanical anchors for prestressed FRP strips allowed higher flexural loads and ductile behavior enhancement. It was also concluded that the anchored beams experienced a rupture in the FRP strips as the anchors were successfully preventing the FRP strips from debonding. Kim et al. [4] replaced the mechanical anchors for prestressed FRP sheets with nonmetallic anchorages (non-anchored U-wrap and anchored U-wrap). The test results concluded the efficiency of the replaced nonmetallic anchors at maintaining a considerable amount of prestressing force in FRP sheets. Bae and Belarbi [5] determined the improving effect of three mechanical anchorage types in shear-strengthened RC beams. Piyong et al. [6] and Smith et al. [7] used glass fiber spikes to enhance the flexural performance of concrete slabs strengthened with nonprestressed and prestressed carbon-FRP sheets. The test results indicated that the glass anchor spikes significantly increased the ultimate strength and the ductility of the strengthened slabs. The rupture of fibers was captured at the ultimate stage instead of the fibers debonding. Smith et al. [7], Ekenel et al. [8], and Ekenel and Myers [9] conducted studies on the glass spikes to anchor FRP sheets for flexural strengthening RC beams. Two of the studies determined the effectiveness of using glass anchor spikes on upgrading the flexural strength of RC beams. However, the anchor spikes did not contribute to the flexural stiffness of strengthened RC beams subjected to fatigue loading [9]. Despite all of the above research, this new generation of FRCM composite materials are still under investigation to be implemented for repair and strengthening of infrastructure systems. The FRCM composite material consists of a fabric made of either carbon, polyparaphenylene benzobisoxazole (PBO), or glass and a cement based mortar. This type of composite has distinct properties that overcome the FRP composites such as resistance to elevated temperature, non-toxic fume installation, compatibility with structural materials (concrete and masonry), and high impact resistance [10, 11, 12]. The FRCM composites have been investigated through many researches to determine its effectiveness in flexure, shear, and fatigue performance [10, 11, 12, 13, 14, 15, 16]. Experimental studies determined that increasing the reinforcement ratio of FRCM composite was not proportionally increased the load carrying capacities of RC members. The debonding failure mode was announced for all repaired or strengthened RC members with multilayers of FRCM [10, 11, 12, 13, 14, 15, 16]. Thus, experimental studies are necessary to examine the effectiveness of using anchorage systems with FRCM system. However, limited experimental researches are presented here. A novel textile-based anchor was developed by Tetta et al. [17] and used to improve the textile reinforced mortar (TRM) composite in the shear strengthening of T-section RC beams. The novel anchor consisted of fan-shaped textile strips that doweled into concrete at one end and distributed over the U-wrapped strengthening system. The fan strips served for the distribution of stresses between the textile reinforcements and the anchored strips. The dowel part of the anchor served for fixing the fan-shaped anchors into the concrete mass. The effect of the anchorage number, position of anchors, textile type, and textile layers was studied. The test results defined the great influence of textile anchorage in shear strength gain. Younis et al. [18] studied different FRCM systems for shear strengthening application. Some beams were strengthened with FRCM system and anchored at the top and bottom with FRP plate in order to increase the efficiency of FRCM in shear enhancement. In spite of using anchorage, the measured load carrying capacity of the anchored FRCM was insignificant. Marcinczak and Trapko [19] evaluated the influence of using U-wrapped stirrups of FRCM in shear strengthening of beams. The U-stirrups anchorage was able to increase the shear capacity of the strengthened beams in the range of 15% to 27% of that of unstrengthen beam. However, the proposed method of anchoring did not ensure a complete utilization of tensile strength of the PBO mesh. More work are in need to understand the effect of using anchorage systems and which types would be an effective technique. This work represents a pilot study to investigate the effect of using different anchorage systems to improve the flexural performance of strengthened beams with an FRCM system.

2. Research Significance

This work is a pilot study on using anchorage systems with cement-based composites. The idea behind using anchorage systems is based on the observed debonding failure mode in many experimental works for strengthened RC beams with multilayers of FRCM composite. The aims of this study were to determine the influence of anchorage systems on increasing the flexural performance of FRCM composite either by delay or prevent the debonding in FRCM composite and to determine whether the anchorage systems would influence the failure type of the FRCM composite or not.

3. Experimental Work

3.1 Material properties

The experimental program included a total of seven medium-scale beams. The RC beams had nominal cross-sectional dimensions of 305 mm (12-in.) depth and 203 mm (8-in.) width with a total length of 2.133 m (7-ft). The concrete was ready-mixed concrete with 28-day target strength of 41.4 MPa (6,000 psi). Concrete cylinders that had a diameter of 100 mm (4-in.) and a height of 200 mm (8-in.) were used to specify the concrete properties. The compressive strength and young's modulus of elasticity of concrete were based on ASTM C39 [20] and ASTM C469 [21], respectively. The concrete's average compressive strength of three tested cylinders was about 45.5 MPa (6,600 psi) at the date of the beam specimens' testing, and the concrete's modulus of elasticity was about 36,425 MPa (5,283 ksi). Steel rebar of 10 mm (No. 3) in diameter was used as longitudinal and transverse reinforcements. The tensile yield and ultimate strengths were determined by testing three coupon specimens based on ASTM A370 [22]. The average yield strength of three coupons was 482 MPa (70 ksi), and the average ultimate rupture of three coupons was 726 MPa (105 ksi). The polyparaphenylene benzobisoxazole (PBO) fabric was the proposed type of FRCM composite in this study. The PBO fabric was made of 5 mm (0.2-in.) and 3 mm (0.125-in.) wide yarns in the longitudinal and transverse directions, respectively, as shown in Fig.1.1. The free space between the yarns was roughly 5 mm (0.2-in.) and 22 mm (0.9-in.) in the longitudinal and transverse directions, respectively, and the nominal thickness of the yarns was 0.2 mm (0.008-in.) and 0.12 mm (0.045-in.) in the longitudinal and transverse directions, respectively. The cement-based mortar was made of a combination of Portland cement, silica fume, and fly ash as a binder. It had less than 5 percent polymer. The cement-based mortar also contained glass fibers to improve the bond between the PBO mesh and the cement mortar and to provide better tensile properties. The other type of cement mortar was used as a base mortar to level the concrete surface, close the crack opening, and improve the bond performance between the FRCM composite and the concrete substrate. The base mortar was made of fine cement particles and silica fume. The base mortar contained polypropylene fibers to bridge concrete cracks and to improve the bond performance of the FRCM composite-concrete surfaces. All FRCM composite materials are presented in Fig. 1. The PBO fabric was used as external flexure reinforcement with a tensile strength of 5,800 MPa (840 ksi), elastic modulus of 270,000 MPa (39,160 ksi), and ultimate strain of 0.0215 mm/mm (in./in.). All of the beams were designed to fail in flexure based on the ACI 549-13 [23] and ACI 318-14 [24]. A typical beam dimensions and its internal reinforcement details are presented in Fig. 2.

3.2 Strengthening schemes

Two different anchorage systems were considered in this study. The first anchorage system was the glass spike. As mentioned above, the glass spike was used in previous research and successfully enhanced the FRP composite’s flexural performance [6, 9]. The second anchorage system was a novel U-wrapped PBO strip. A new technique of anchoring the U-wrapped PBO strips is proposed to inhibit the debonding of the U-wrapped PBO strip by transferring the stresses into concrete, as presented in section 3.3. Two strengthening reinforcement ratio were considered here. Three RC beams were strengthened with two FRCM sheets and the other three beams were strengthened with three FRCM sheets. Two sheets of FRCM strengthening with anchorage systems were selected in order to determine its ability to replace four FRCM sheets. Four sheets of FRCM strengthening with anchoring systems were designed in order to delay the premature debonding failure of four FRCM sheets and examine higher order enhancements in flexural performance. Table 1 summarizes the test matrix of seven RC beams. One RC beam specimen served as the control beam. The other beam specimens were divided into two groups of three beam specimens. In group one, beams were strengthened with two sheets of FRCM composite. In group two, beams were strengthened with four sheets of FRCM composite. In each group, one beam was strengthened with FRCM composite without anchorages, one beam was strengthened with FRCM composite and anchored with glass spikes, and one beam was strengthened with FRCM composite and anchored with U-wrapped PBO strips. Seven anchors were spaced along the span length of the strengthened beams. The number of anchors was distributed through the beam span length to reduce the stress concertation at the maximum moment regions and at the ends of FRCM strengthening where not enough development length was provided. The center-to-center spacing between the anchors was 280 mm (11-in.). The distribution and detail of glass spikes are presented in Fig. 3a. The central position of glass spikes were extended 25.4 mm (1.0-in.) from the center line of RC beams in a staggered form in order to prevent drilling at the location of longitudinal rebar. The glass spike width was 150 mm (6-in.). The U-wrapped PBO strips' width was 114 mm (4.5-in.). The U-wrapped PBO strips were anchored into the sides of RC beams at a depth of 100 mm (4.0-in.) from the top concrete surface to be away from the maximum tensile and compressive stresses areas, as shown in Fig. 3b. The anchor material mechanical properties are presented in Table 2. The detailed schemes for anchorage systems are presented in Fig. 4. The anchor's diameter was 15 mm (0.6-in.) and the embedded length inside the concrete was 50 mm (2-in.) for each anchorage system.

3.3 Anchorage systems preparation and strengthening application

Before the FRCM strengthening system was applied on the RC beams' substrates, all beams were pre-cracked to 65% of their expected ultimate load capacity. This level of load represented an approximate service loading level based on the ACI 549-13 [23]. Then, the beams were sandblasted to remove the smooth layer of concrete surface and provide better surface to adhere the FRCM composite as recommended by the ACI 549-13 [23]. The edges of two RC beams were rounded to 20 mm (0.75-in.) in order to reduce the stress concentrations around the U-wrapped PBO strips as recommended by the ACI 549-13 [23]. Holes that were 50 mm (2-in.) long and 18 mm (0.7-in.) in diameter were drilled into the concrete at the desired points for installing the anchorage systems. All of the holes were cleaned with air pressure and all of the beams' surfaces were vacuumed to remove the dust. The anchorage systems were prepared as follows. The first anchor type was the glass spike. The glass spike was made by cutting a strip of the glass filament from the roving roll and folding several times to provide the required diameter, as shown in Fig. 5a. The folded ends of the glass strip were cut to have a total length of 254 mm (10-in.). One end was saturated using an epoxy agent (Mbrace^{TM}-saturant) to be doweled inside the concrete hole with a bond length of 50 mm (2-in.), as shown in Fig. 5 (b and c). The glass spikes left to be set for more than four hours at a laboratory temperature based on manufacture requirement. Then the glass spikes were attached to the concrete holes by epoxy agent and left to be set for four hours, as shown in Fig. 5d. After that, the installation of the FRCM composite began by wetting the concrete substrate to eliminate the water absorption from the applied cement-based mortar. The FRCM strengthening in the form of two or four PBO sheets was applied to the concrete substrate. The cement-based mortar was used successively to attach the PBO sheets, as shown in Fig. 6 (a, b, and c). The PBO sheets had a width of 200 mm (7.5- in.) and a length of 1830 mm (72-in.). The glass anchor spikes were fanned over the last layer of the PBO sheet in a circular pattern, as shown in Fig. 6d, and covered with the cement-based mortar, as shown in Fig. 6e.

The second anchor type was the novel U-wrapped PBO strip. The U-wrapped PBO strip was made by cutting the PBO fabric in strips and removing the PBO fabric in the transverse direction, as shown in Fig. 7 (a and b). Then, the ends of the PBO strips were saturated with epoxy agent (Mbrace-saturant) for a length of 50 mm (2-in.) to be anchored in RC beams, as shown in Fig. 7 (c, d, and e). The installation of the U-wrapped PBO strips was done immediately after applying the successive layers of the FRCM composite, as shown in Fig. 8 (a, b, and c). Then, the U-wrapped PBO strips' ends were adhered into concrete holes using a high viscosity gel epoxy (MasterEmaco, ADH 1420), as shown in Fig. 8d. The final shape of the U-wrapped PBO strip is presented in Fig. 8e. All of the strengthened RC beams were cured with water for three days and covered with plastic sheets to prevent the loss of moisture. Then, the strengthened RC beams were cured under laboratory conditions for 25 additional days before testing. The curing steps of the applied FRCM composite and anchorage systems were performed in the regards of manufactures recommendation.

4. Test Set-up and Instrumentation

Four-point loading was selected to determine the anchorages' efficiency. The loads were applied on a displacement rate control of 1.3 mm/minute (0.05 in./min). A linear variable differential transducer (LVDT) was used to measure the displacement in the RC beams. Strain gauges were used to determine the strain reading of the internal longitudinal rebar and the external applied FRCM composite. The distribution schemes of strain gauges are presented in Fig. 9.

For all RC beams, two strain gauges were bonded to the longitudinal rebar at the mid-span, two strain gauges were bonded to first and last sheets of the FRCM composite at the mid-span, and three strain gauges were attached to the external surface of the FRCM composite (at the mid-span and at the ends), as shown in Fig. 9a. For the U-wrapped PBO strips, five strain gauges were attached to each PBO strip to determine its effective strain at the bottom, the edge region, and area close to the anchored ends, as shown in Fig. 9b. The data acquisition system was used to record the load displacement curve and the strain gauge readings.

5. Experimental Results

5.1 Load displacement

The load displacement curves of tested beams are presented in Fig. 10. Table 3 includes the key results: ultimate load, percentage increase in ultimate load, displacement at yielding of rebar, displacement at ultimate load, and displacement ductility index. The load displacement response for the control RC beam was a classic response. The rebar yielded at 72 kN (16 kips) followed by an ultimate load of 122 kN (27.4 kips). Then, the load displacement curve turned to the plastic-ductile response and the concrete crushing terminated the test. The strengthened beams exhibited a gain in the flexure strength through the inelastic loading stage followed by a drop in their carrying loads as the FRCM strengthening and anchorage systems reached their failure loads. Then, the strengthened beams went through the plastic-ductile stage similar to the control beam. The strengthened beams with two and four PBO sheets produced higher ultimate loads of 154 kN (34.6 kips) and 141 kN (31.6 kips), respectively. The anchored beams with glass spikes carried an ultimate load of 147 kN (33 kips) and 154 kN (34.6 Kips) for two and four PBO sheets, respectively. The anchored U-wrapped beams supported an ultimate load of 148 kN (33.3 kips) and 175 kN (39.2 kips) for two and four PBO sheets, respectively. It is concluded that the anchorage systems were more effective when a higher reinforcement ratio of PBO sheets was provided. As a measurement for the ductility performance of the strengthened beams with and without anchorages, the displacement ductility index was determined. The displacement ductility index represented the ratio of the beam's displacement at the ultimate load to the beam's displacement at the yielded load. The strengthened beams with and without anchorages obtained lower displacements at the yielded and ultimate load stages with respect to the control beam. However, most strengthened beams retained 65% to 87% displacement ductility index of that of the control beam with the exception of the strengthened beam with four PBO sheets which had only 45% displacement ductility index of that of the control beam due to the premature FRCM debonding. In addition, the effectiveness of the anchorage systems on the displacement ductility performance increased for the strengthened beams with four PBO sheets than two PBO sheets. Thus, the anchorage systems had a better ductile behavior as the FRCM reinforcement ratio increased.

5.2 Crack pattern, failure mode, and number of sheets

All of the beams failed due to flexural cracks that observed from the tensile face toward the top face of the beams, preceded by FRCM strengthening failure, as shown in Fig. 11. In addition, concrete crushing was noticed at the final loading stage. The non-anchored beams that were strengthened with two or four sheets of FRCM composite exhibited intermediate debonding at the maximum loaded area and the endplate debonding at the free end. The debonding was at the interface between the PBO sheets and the cementitious matrix. The anchored beam with glass spikes that was strengthened with two sheets of FRCM composite exhibited a slippage of the PBO sheets out of the cementitious matrix at the mid-span with no debonding of the PBO sheets along the span length. The anchored beam with glass spikes that was strengthened with four sheets of FRCM composite was revealed intermediate debonding and endplate debonding of the PBO sheets out of the cementitious matrix. The anchored beams with U-wrapped PBO strips that were strengthened with two sheets of FRCM composite exhibited a slippage of the PBO sheets and U-wrapped PBO strips out of the cementitious matrix at the mid-span. A slippage failure mode of the PBO sheet usually indicates that the PBO fabric developed a higher percentage of its tensile strength. In such a case, anchorage systems could not contribute more in upgrading the flexural performance of strengthened beams. However, the mode of failure was improved from intermediate debonding and end plate debonding to the slippage of PBO sheets, while anchorage systems contributed to delay the premature debonding failure mode and increase the ultimate loads in strengthened beams with four PBO sheets. The ultimate load of the strengthened beam with four PBO sheets and anchored with glass spikes was 10% higher than the non-anchored strengthened beam with four PBO sheets. The ultimate load of the strengthened beam with four PBO sheets and anchored with U-wrapped PBO strips was 24% higher than the non-anchored strengthened beam with four PBO sheets.

5.3 Anchorage's configuration and material

Test results of anchored beams determined different flexural performance. The external reinforcement ratio of the PBO sheets was interfered with the contribution of the anchorage systems. The glass spikes contributed to reduce the stress concentration in the direction of the PBO sheets and delayed the debonding failure mode. The anchored U-wrapped PBO strips performance verified the research idea of relying on the high-tensile strength of PBO strips. The ends of the PBO strips which anchored into the concrete prevented the debonding of the U-wrapped PBO strips, and developed a slippage failure mode in the PBO strips. The anchored U-wrapped PBO strips resulted in greater enhancement than glass spikes in terms of the ultimate load and the displacement ductility of the strengthened beam with four PBO sheets. The anchorage and confinement of the anchored U-wrapped PBO strips contributed to its greater impact. In addition, the anchors' material type could also play role in the efficiency of the anchorage systems. The PBO strips had higher tensile properties than glass spikes, which could be another reason why the U-wrapped PBO strips performed better. More experimental investigation would assist in a proper selection of the anchorage systems in terms of the material type and configuration.

5.4 Strain measurements

Measurements of the strains in the rebar, FRCM strengthening, and U-wrapped PBO strips are presented in Table 4. The strain reading of the rebar determined that it was yielded in all tested beams. The ultimate strain in the rebar ranged between 0.005 mm/mm (in./in.) and 0.006 mm/mm (in./in.) based on the measurement of two beams. The strain reading in the first applied PBO sheet at mid-span ranged between 0.002

mm/mm (in./in.) and 0.005 mm/mm (in./in.), while higher strain readings were obtained in the last applied PBO sheet at mid-span. The anchorage systems reduced the strain reading of the PBO sheets at the edges. Glass spikes reduced the strain reading of the PBO sheets by half of that measured in strengthened beams without glass spikes. The U-wrapped PBO strips at the edges showed zero strain reading in the PBO sheets. The non-strain reading of the PBO sheets at the edges indicated the influence of the anchorage systems in preventing the PBO sheets' endplate debonding.

6. Conclusions

Anchorage systems can be used in order to delay or prevent debonding of the composite materials from concrete substrate in flexural strengthening or repairing applications. In such applications, the debonding can occur at the maximum moment regions or when not enough development length of strengthening systems can be provided. Prevent the debonding would maintain the structural efficiency. The effectiveness of two anchorage systems in increasing the strength and displacement ductility of FRCM strengthened RC beams is reported as follows:

1. The anchorage systems can enhance the flexural performance of strengthened RC beams with FRCM composite based on the provided strengthening reinforcement ratio.
2. The anchorage systems successfully prohibited the endplate debonding failure mode where not enough development length could be provided.
3. The anchorage systems were proved to prevent or delay the intermediate debonding failure mode in the FRCM strengthening based on its reinforcement ratio.

4. The non-anchored and anchored strengthened beams with two PBO sheets obtained the same flexural strength but the anchorage systems changed the mode of failure from a debonding failure to a slippage failure of the PBO sheets.
5. The novel anchored U-wrapped PBO strips increased the ultimate load by 24% more than the non-anchored strengthened beam with four PBO sheets.
6. The anchored U-wrapped PBO strip had a superior flexural enhancement compared to the glass spike due to its high tensile property and confinement action.

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(a) Group1, beams with 2-ply

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479 **Fig. 11** - Crack pattern and failure mode

Table 1- Test matrix for strengthening configuration and anchorage

Specimen ID	Layers number	Anchors number	Anchorage configuration	Anchored layer	Anchor type
Con-RC					
G1-2	2				
G1-2-Glass	2	7	Along the span length	2	Glass
G1-2-PBO	2	7	Along the span length	2	PBO
G2-4	4				
G2-4-Glass	4	7	Along the span length	4	Glass
G2-4-PBO	4	7	Along the span length	4	PBO

Table 2. Anchor material properties

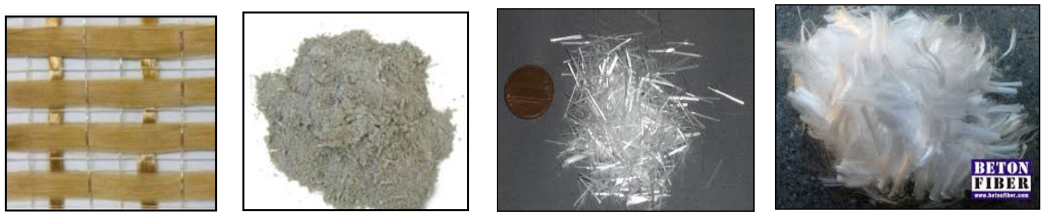
Reinforcement type	Tensile strength MPa (ksi)	Elastic modulus MPa (ksi)	Ultimate strain mm/mm (in./in.)
PBO fibers, Ruredil Company	5,800 (840)	270,000 (39,160)	0.0215
Glass fibers, D-BASF Company	3,400 (490)	73 (10)	0.045

Table 3. Ultimate loads and Displacments

Specimen ID	Experimental ultimate load, kN (kips)	% Increase in load carrying Capacity	Yield displacement (δy) mm (in.)	Ultimate displacement (δu) mm (in.)	Displacement ductility index (δu/δy)
Con-RC	122 (27.4)		6.6 (0.26)	51.0 (2.0)	7.7
G1-2	154 (34.6)	26%	4.3 (0.17)	25.4 (1.0)	5.9
G1-2-Glass	146 (33.0)	20%	4.6 (0.18)	30.5 (1.2)	6.7
G1-2-FRCM	148 (33.3)	22%	5.1 (0.2)	25.4 (1.0)	5.0
G2-4	141 (31.6)	15%	5.1 (0.2)	17.8 (0.7)	3.5
G2-4-Glass	154 (34.6)	26%	4.6 (0.18)	28 (1.1)	6.1
G2-4-FRCM	175 (39.2)	43%	4.1 (0.16)	25.4 (1.0)	6.3

Table 4. Strain readings in rebars, FRCM sheets, and anchorage

Specimen ID	Strain reading, mm/mm (in./in.)					
	Rebar	FRCM sheets at mid-span		FRCM at edge	U-wrapped PBO	
	Mid-span	First sheet	Last sheet	Last sheet	Center	Edge
Con-RC	0.005					
G1-2		0.002	0.005	0.007		
G1-2-Glass		0.005	0.010	0.004		
G1-2-FRCM		0.005	0.004		0.004	0.000
G2-4	0.006		0.006	0.005		
G2-4-Glass		0.004	0.006	0.003		
G2-4-FRCM			0.010		0.010	0.000



(a) (b) (c) (d)

Fig. 1 - FRCM composite materials: (a) Polyparaphenylene benzobisoxazole (PBO) mesh, (b) Inorganic Matrix, (c) Glass fiber, and (d) Polypropylene fiber

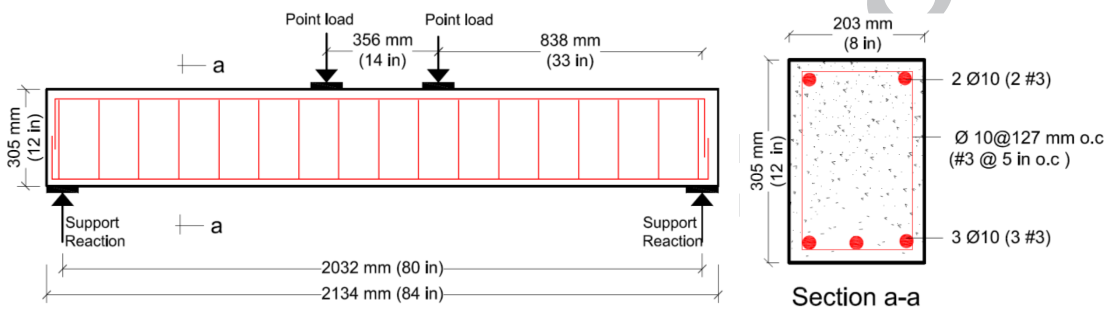
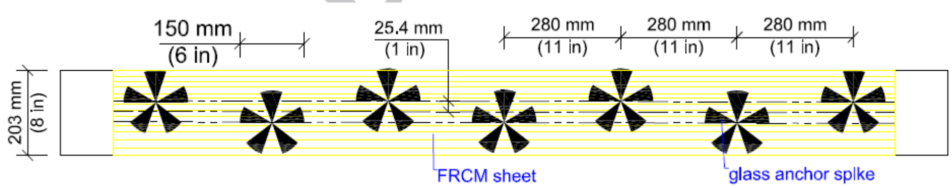
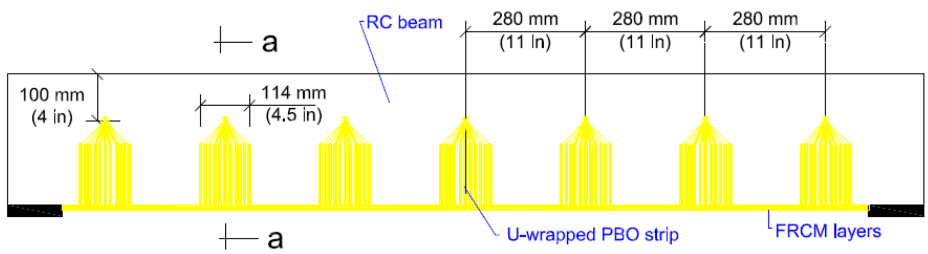


Fig. 2 - Typical geometry and reinforcements of the beam specimen

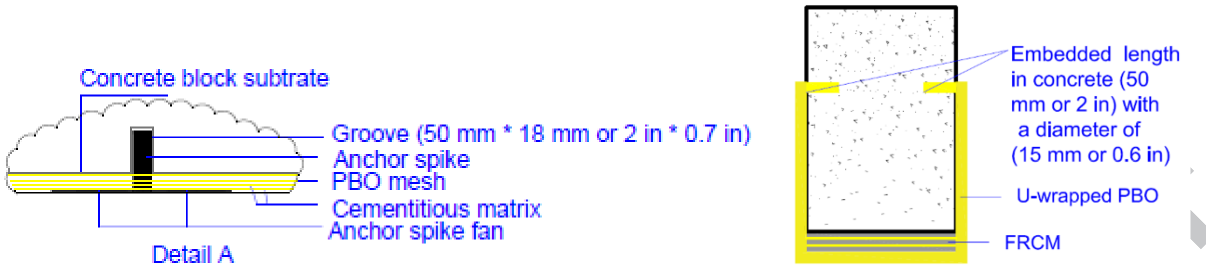


(a) Glass anchor spikes across the span, bottom view



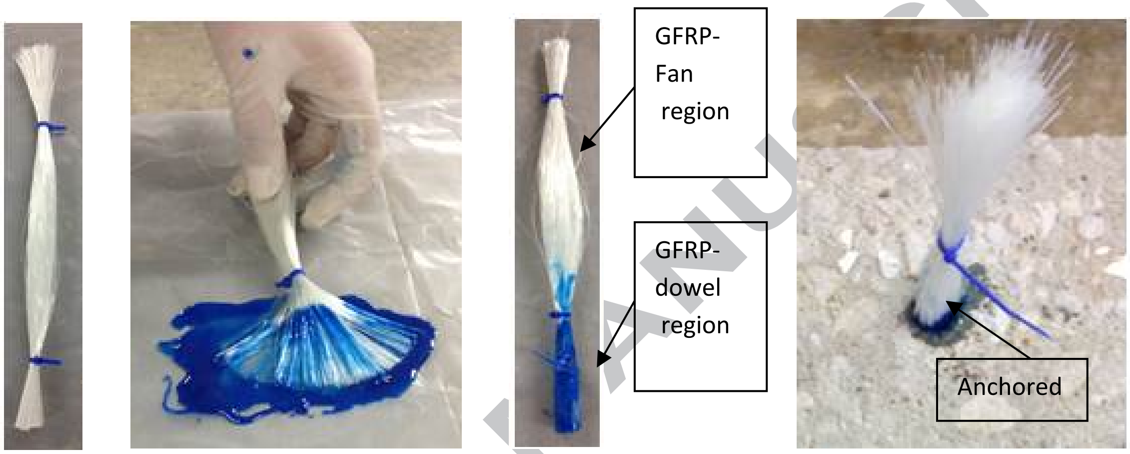
(b) U-wrapped PBO-strips across the span, side view

Fig. 3 - Anchorage systems distribution



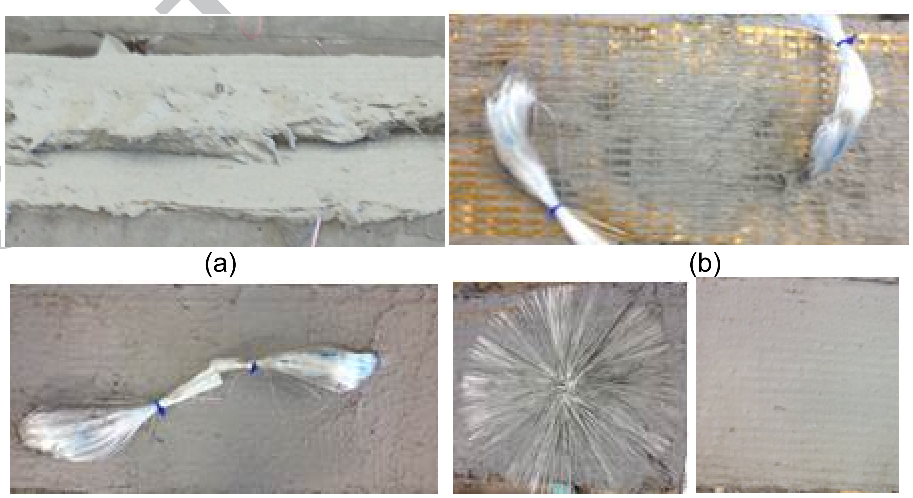
(a) Glass spike (b) Section a-a, U-wrapped PBO strip

Fig. 4 - Anchorage systems' details



(a) (b) (c) (d)

Fig. 5 - Glass spikes preparation: (a) Folded glass fabric, (b) Saturation of glass-fabric end, (c) GFlass spike, and (d) Anchor glass spike inside concrete hole



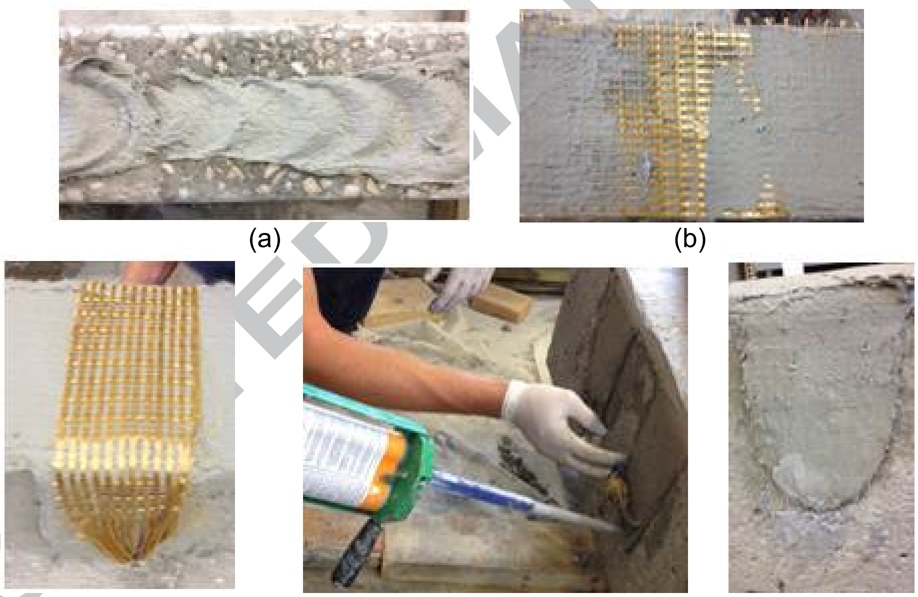
(a) (b)

(c) (d) (e)

Fig. 6 - FRCM composite application with glass spikes: (a) Cement-based mortar application, (b) PBO-sheet embedment into mortar, (c) Covering PBO-sheet with mortar, (d) Fan glass spikes, and (e) Covering glass spikes with mortar

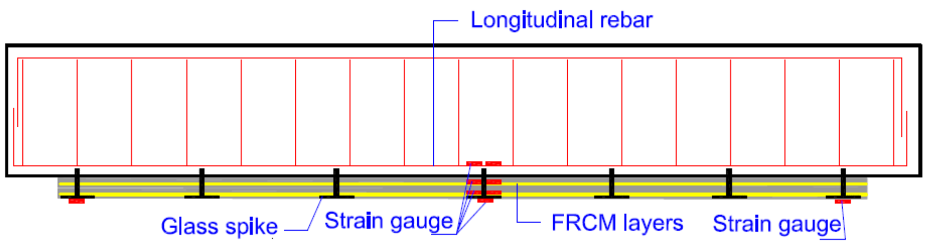
(a) (b) (c) (d) (e)

Fig. 7 - Anchored U-wrapped PBO strip preparation: (a) Removal transverse PBO- fabrics, (b) Geometrical shape of U-wrapped PBO strip, (c) PBO-fabric ends saturation, (d) Injection of saturator around PBO strip's end, and (e) U-wrapped PBO strip's end shape

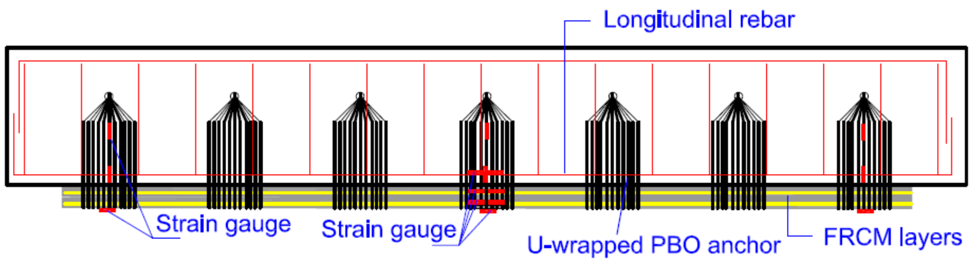


(a) (b) (c) (d) (e)

Fig. 8 - FRCM composite application with anchored U-wrapped PBO strips: (a) Placement of cement-based mortar, (b) PBO-sheet embedment into mortar, (c) Application of U-wrapped PBO strip, (d) Injection of gel epoxy into concrete hole, and (e) Final shape of anchored U-wrapped PBO strip

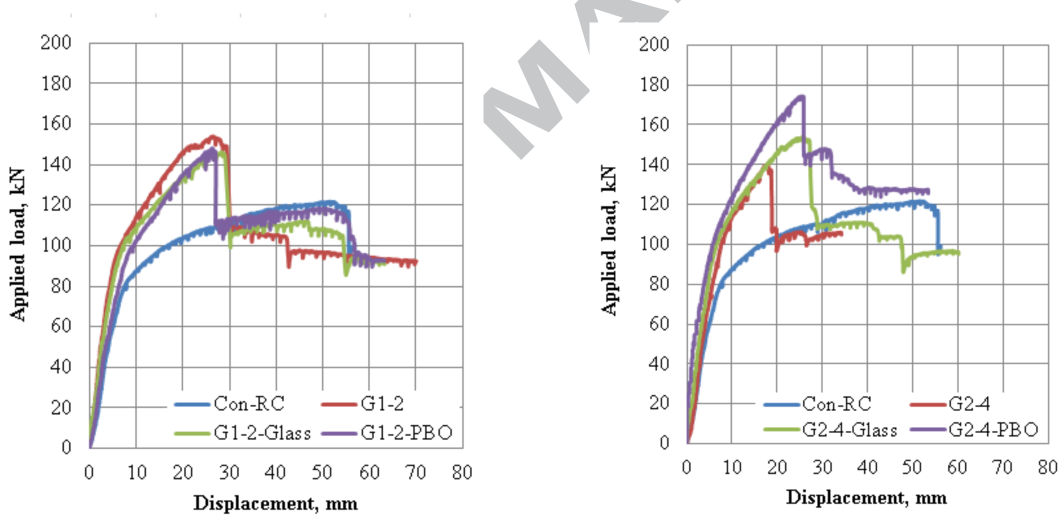


(a) Strain gauges distribution for anchored RC beams with glass spike



(b) Strain gauges distribution for anchored RC beams with U-wrapped PBO

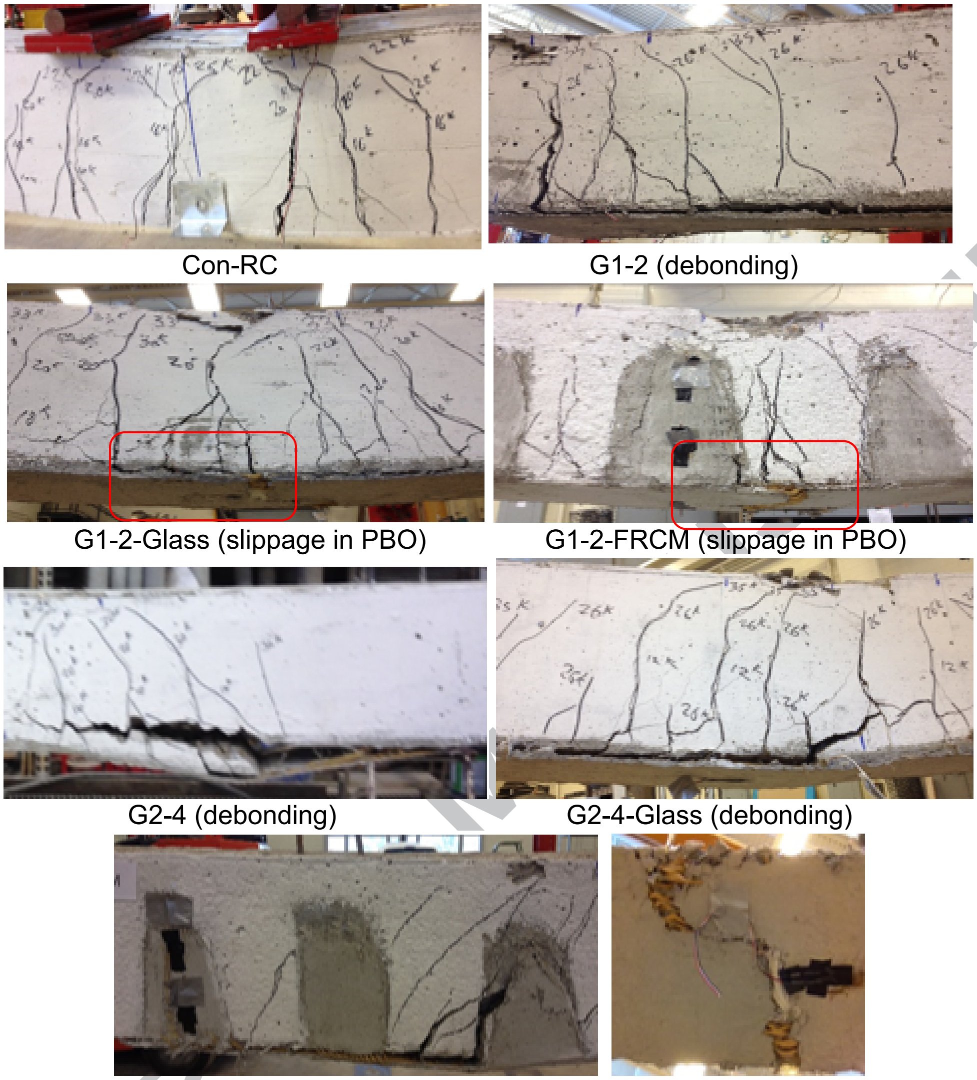
Fig. 9 - Strain gauges scheme



(a) Group1, beams with 2-ply (b) Group2, beams with 4-ply

Conversion units: 1-in. = 25.4 mm; 1 Kip = 4.45 kN

Fig. 10 - Load displacement curves



Con-RC G1-2 (debonding)

G1-2-Glass (slippage in PBO) G1-2-FRCM (slippage in PBO)

G2-4 (debonding) G2-4-Glass (debonding)

G2-4-FRCM (debonding) Slippage in PBO

Fig. 11 - Crack pattern and failure mode