



Tensile capacity of FRP anchors in connecting FRP and TRM sheets to concrete



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ABSTRACT

This paper investigates the effectiveness of carbon fiber spike anchors as a means of anchoring externally bonded (EB) fiber-reinforced polymers (FRP) and textile reinforced mortar (TRM) sheets into concrete. The investigation employs experimental work, which includes reinforced concrete (RC) columns strengthened with various configurations of EB FRP and TRM sheets connected to RC footings via carbon fiber spike anchors. The fiber spikes have two parts: the anchor part and the fan part. The anchor part is a bar-type dowel component that is epoxy pre-impregnated and inserted into epoxy filled holes within the footing. The fan part was impregnated in-situ and fanned out over and bonded to the EB reinforcement of the column. The connections were tested by pulling the columns upwards, thus applying tensile forces to the connection system. The direct tensile capacity of the anchors was determined for a number of variables including the size and number of anchors, the bonding agent and the type and amount of EB reinforcement. It is concluded that, with appropriate anchorage into concrete, the carbon fiber spike anchor is an effective anchorage system, and therefore, could be used in a range of strengthening applications to prevent premature delamination of FRP and TRM sheets from concrete surfaces.

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1. Introduction and background

The use of fiber-reinforced polymers (FRP) as strengthening material for reinforced concrete (RC) structures has become very popular, due to their favorable properties (low weight, easy handling and application, high strength, immunity to corrosion, minimal disruption of occupancy). In an attempt to alleviate some problems associated with FRP, especially with regards to epoxy resins, researchers have introduced the concept of combining advanced fibers in the form of textiles with inorganic matrices, e.g. cement-based mortars. The so-called textile reinforced mortars (TRM) have been reported as an extremely promising solution in many cases of strengthening and seismic retrofitting RC structures e.g., [1,2,3,4,5,29,32].

Both externally bonded (EB) FRP and textile-reinforced mortar (TRM) systems have been successfully used for the flexural and shear strengthening of concrete members, however, the premature delamination of FRP or TRM sheets from the concrete surface limits the effectiveness of the technique. To prevent or delay the delamination of the EB reinforcement, effective anchorage of the FRP or TRM might be improved with the use of various anchorage systems.

Anchorage systems include the use of metallic bolts or FRP anchors. Metallic anchorages have been investigated by several researchers (e.g. [10,30]) and despite their effectiveness; they are heavy, incompatible with the composite materials and require protection against corrosion. Anchors made using FRP on the other hand, also known as FRP spike anchors or FRP anchors, are non-corrosive and can be applied to a wide variety of structural shapes such as beams, slabs, columns, infilled RC frames and walls.

FRP anchors comprise bundles of carbon, glass or aramid fibers (or rolled fiber sheets) which can be distinguished in two parts: the anchored part and the fan part. The anchor part is pre-impregnated bar-type anchor dowel component which is inserted into epoxy filled holes. The anchor fan component is impregnated in-situ and fanned out over the FRP sheets. Fig. 1 illustrates examples of using FRP anchors combined with FRP and TRM sheets.

FRP spike anchors are very practical to use and have received the attention of few investigations looking into bond aspects [7,9,11,25]; confinement of columns [14,15]; flexural strengthening of beams or slabs [8,26,31]; strengthening to provide continuity of longitudinal reinforcement in continuous RC beams [16]; flexural strengthening of columns [33]; shear strengthening of columns [19,24]; shear strengthening of T-beams [12,17,21] and strengthening of infilled RC frames with Textile-based anchors [22]. A state-of-the-art review on the anchorage devices used to

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improve the efficiency of EB FRP systems was very recently made by [13].

Studies to determine the tensile capacity of spike anchors are limited to these of Ozdemir and Akyuz [28], Ozbakkaloglu and Saatcioglu [27] and Kim and Smith [18]. Ozdemir and Akyuz investigated experimentally the tensile capacity of FRP anchors embedded into concrete, with parameters under investigation being the anchorage depth, the compressive strength of concrete, the size of the anchor hole and quantity of the anchor fibers. They concluded that of great importance was the anchorage depth and the quantity of anchor fibers. Ozbakkaloglu and Saatcioglu [27] investigated experimentally the tensile behavior of FRP anchors in concrete and concluded that FRP anchors can be designed to achieve high pullout capacities and hence prevent or delay the delamination of EB FRP sheets. Kim and Smith [18] presented analytical models to quantify the pullout strength of FRP anchors and proposed simple and rational pullout strength models for FRP anchors to be used in design. Both of the studies above were focused on the pullout capacity of anchors embedded in concrete with the tensile load applied directly onto the anchor head.

In this paper the authors investigate for the first time the direct tensile capacity of FRP spike anchors inserted into concrete holes whereas the protruding fibers are fanned out over the layers of the FRP or TRM sheet. This anchoring system is investigated herein on a real-scale and systematic way by examining: the weight (or nominal diameter) of anchors; the number of anchors; the type of fiber and the bonding agent used to bind the sheet-anchor system.

2. Experimental programme

2.1. Test specimens and experimental parameters

The experimental programme aimed to study the tensile capacity of FRP spike anchors in connecting concrete members with EB FRP or TRM sheets and to compare the effectiveness of different

anchorage schemes. A total of eight column and foundation RC elements with no reinforcement crossing the interface between the column and foundation block were connected with FRP anchors (Fig. 2). The specimens were tested under direct uniaxial tension applied to the column part (Fig. 2a). The column element had a cross-section of 200×200 mm. The foundation blocks were heavily reinforced and had a cross-section of 400×400 mm. The columns were connected to the foundation blocks by means of a system comprising FRP anchors and composite material sheets. The columns were reinforced longitudinally with four 12 mm-diameter deformed bars and 8 mm diameter deformed stirrups, at 60 mm centers and closed with 135-degree hooks. The geometry of a typical cross section is shown in Fig. 2b.

The specimens were designed such that the effect of a series of parameters on the effectiveness of FRP anchors-composite sheets system could be investigated, namely the number of anchors, the anchor cross sectional area, the type of EB sheets connected with the spike anchors, the bonding agent used to bind the sheet-anchor system and the presence of external confinement with composite material jacket. A description of the specimens follows next, supported by Table 1 and Fig. 3.

- Specimen **F2_2Φ6** was strengthened with two 200 mm wide epoxy-impregnated carbon fiber sheets on each of the two opposite sides of the column specimen. The CFRP sheet extended throughout the height (600 mm) of the column specimen and was anchored at the base block with two carbon fiber spike anchors on each side of a nominal diameter of 6.25 mm (Fig. 3a). The procedure for calculating the weight of the anchors corresponding to a nominal diameter follows in the next section.
- Specimen **F2_1Φ9** was strengthened as **F2_2Φ6**, but with one instead of two anchors per side, with approximately the same cross sectional area of fibers (nominal diameter of 9.25 mm, Fig. 3b).

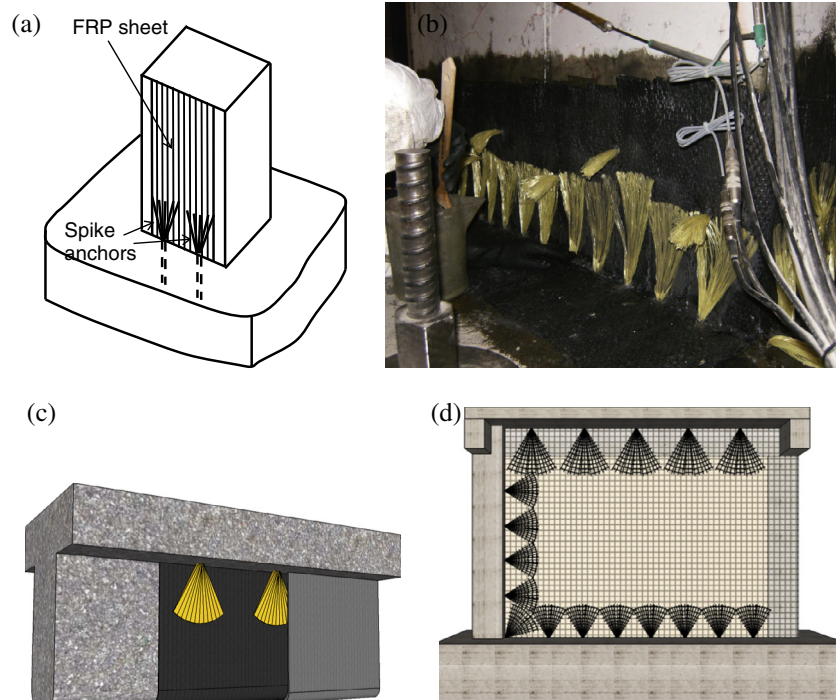


Fig. 1. (a) Flexural strengthening of RC column with EB FRP sheets combined with spike anchors [6]. (b) Flexural strengthening of a bridge pier with deficient lap splices with EB carbon fiber sheets combined with aramid spike anchors. (c) FRP anchors in U-jacket shear strengthening of T-beams [20]. (d) Strengthening of Infilled RC Frames with TRMs and textile-based anchors [22,23].

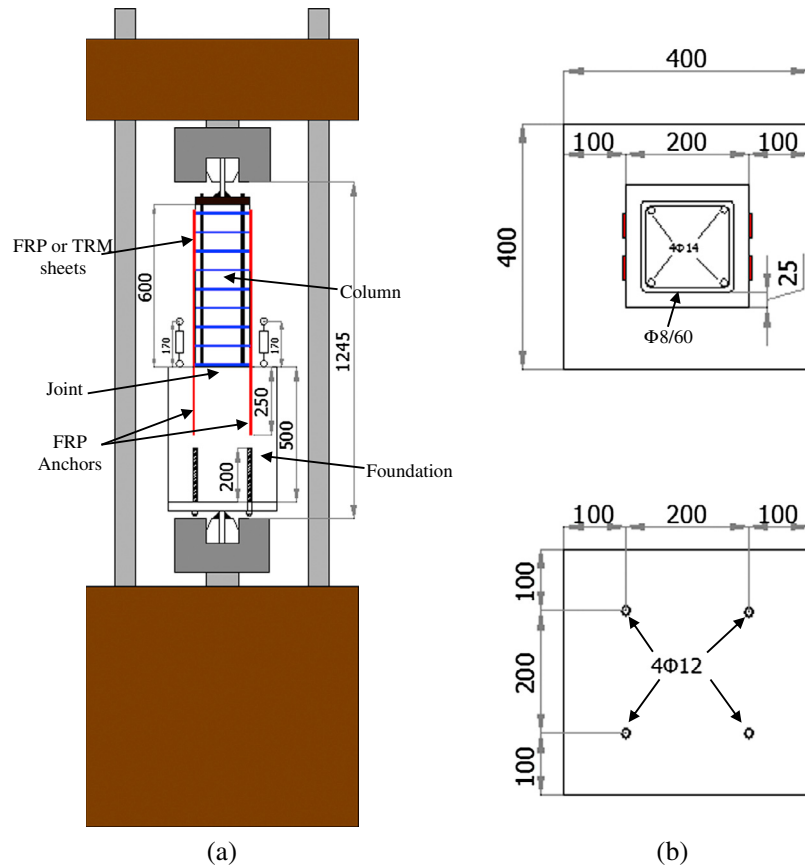


Fig. 2. (a) Schematic of the test setup. (b) Cross-section of columns and concrete blocks (dimensions in mm).

- **F4_1Φ12** was strengthened as **F2_1Φ9**, but with an anchor of 12.7 mm nominal diameter instead of 9.25 mm and four instead of two carbon fiber sheets per side. These anchors were 90% heavier than those in **F2_1Φ9**; hence the anchor cross-sectional area of fibers was almost doubled (Fig. 3c).
- **F4_2Φ9** was strengthened as **F2_1Φ9**, but with two instead of one anchors per side. Correspondingly four instead of two epoxy-impregnated carbon fiber sheets were used on each of the two opposite sides of the column (Fig. 3d).
- Specimen **T4_2Φ6_R** was strengthened with four 200 mm wide epoxy-impregnated textile carbon fiber sheets on each of the two opposite sides of the column. The carbon textile sheet extended throughout the height (600 mm) of the specimen and was anchored at the base block with two carbon fiber spike anchors per side of a nominal diameter of 6.25 mm (Fig. 3e).
- **T4_2Φ6_M** was strengthened as **T4_2Φ6_R**, but mortar instead of epoxy resin was used to bind the textile and the spike anchors (Fig. 3e).
- **T7_2Φ9_RJ** was strengthened as **T4_2Φ6_R**, but with seven instead of four textile carbon fiber sheets per side, whereas the cross sectional area of the anchors used to connect the textile was doubled by using two 9.25 mm instead 6.25 mm nominal diameter anchors. Note that in this specimen the textile was applied in the form of confining TRM jacket [1,3]. In this way the vertical fibers are through the anchors used for the transfer of tensile forces, while the horizontal ones could provide confinement when applied to RC columns (Fig. 3f).
- Finally **T7_2Φ9_MJ** was strengthened as **T7_2Φ9_RJ**, but mortar instead of epoxy resin was used to bind the textile jackets and the spike anchors (Fig. 3f).

In summary, the notation of specimens is **SX_NΦD_B**, where S defines the type of EB reinforcement (F for FRP and T for textile), X denotes the number of EB carbon fiber sheets per column side, N denotes the number of FRP spike anchors used per columns side, D denotes the FRP anchor nominal diameter and B denotes the bonding agent used to bind the carbon textile fiber and spike anchors (R for resin-based and M for mortar-based textiles). Finally, for the two specimens strengthened by means of a textile confining jacket (**T7_2Φ9_RJ**, **T7_2Φ9_MJ**) the letter J was added after letter B to indicate jacketing.

2.2. Strengthening procedure

The concrete surface on each of the two opposite sides of the column specimens was prepared by cleaning and roughening. Fig. 4a shows a prepared specimen. Then a number of unidirectional carbon fiber sheets (two or four) or bidirectional textile carbon fibers sheets (four or seven) 600 mm long and 200 mm wide were bonded (Fig. 4b). The unidirectional sheets were placed with fibers in vertical configuration and were terminated at the column base.

FRP anchors were formed from bundles of initially dry carbon fibers by impregnating them with epoxy, whereas the bar-type anchor dowel component of the anchor was epoxy impregnated 1 day before the retrofitting application to allow for curing of the epoxy, as shown in Fig. 4c. The anchorage of the spike anchors inside the base blocks was done by inserting their ends into 200 mm long by 18 mm diameter holes. A bond length of 200 mm was used in all cases. This was determined to be sufficient

Table 1
Specimens and experimental Parameters.

Specimen notation	Column EB reinforcement		Bonding agent between anchors EBR	FRP anchors				Total anchor area (mm ²)	Area of vertical fibers of the EBR (mm ²)
	Type of carbon fiber	No. of layers per side		Number per side	Diameter (mm)	Area of each anchor (mm ²)	Weight of each anchor (gr/m)		
F2_2Φ6	Unidirectional sheet	2	Resin	2	6.25	30.67	56	122.7	136
F2_1Φ9	Unidirectional sheet	2	Resin	1	9.25	67.2	121	134.4	136
F4_1Φ12	Unidirectional sheet	4	Resin	1	12.7	126.7	228	253.3	272
F4_2Φ9	Unidirectional sheet	4	Resin	2	9.25	67.2	121	268.8	272
T4_2Φ6_R	Bidirectional textile	4	Resin	2	6.25	30.67	56	122.7	152
T4_2Φ6_M	Bidirectional textile	4	Mortar	2	6.25	30.67	56	122.7	152
T7_2Φ9_RJ	Bidirectional textile	7	Resin	2	9.25	67.2	121	268.8	304
T7_2Φ9_MJ	Bidirectional textile	7	Mortar	2	9.25	67.2	121	268.8	304

to avoid anchor pull out failure and ensure anchor rupture failure mode. The holes were filled with epoxy to half of their depths and the anchor dowel component of each anchor was inserted into the holes (Fig. 4d) while the protruding fibers were fanned out over the CFRP sheet (Fig. 4e). Finally the last carbon fiber sheet was applied on the top of the fan as shown in Fig. 4f. Please note that in columns with 4 EB CFRP sheets (or 7 for textile fibers) per side and two anchors, the protruding fibers of two anchors were fanned out over the first and third layers of the CFRP sheet, respectively.

Overall, this method of anchoring was selected in order to transfer the direct tension forces from the composite sheet into the concrete base.

2.3. Test set up and materials

The column 12 mm-diameter longitudinal bars had a yield stress of 538 MPa, a tensile strength of 640 MPa and an ultimate strain equal to 12.7%. The corresponding values for the steel used for stirrups were 521 MPa, 632 MPa and 13.5%. Casting of base blocks and columns were made with the same batches of ready-mixed concrete. The average compressive strength and standard deviation on the day of testing the specimens, measured on 150 × 150 mm cubes, were equal to 26.7 MPa and 1.05 MPa, respectively, entailing that the variability in concrete strength would not affect the column test results.

The unidirectional fiber sheets used as longitudinal reinforcement to be anchored to the concrete block, was a commercial CFRP sheet with a weight of 300 g/m² and a nominal thickness of 0.17 mm. The mean tensile strength and elastic modulus of the fibers (as well as of the sheet when the nominal thickness is used) was taken from data sheets equal to 3790 MPa and 230 GPa, respectively. The carbon fiber sheet was impregnated with a commercial low viscosity structural adhesive (two-part epoxy resin with a mixing ratio 3:1 by weight) with tensile strength of 70 MPa and an elastic modulus of 3.2 GPa (cured 7 days at 23 °C).

For the specimens receiving the bidirectional textile carbon fiber as longitudinal reinforcement, a commercial textile with equal quantity of carbon rovings in two orthogonal directions were used (e.g. Fig. 4b). Each fiber roving was 3-mm wide and the clear spacing between rovings was 7 mm. The weight of carbon fibers in the textiles was 348 g/m, while the nominal thickness of each layer based on the equivalent smeared distribution of fibers was 0.095 mm. For those specimens receiving mortar as a binding material, a commercial inorganic dry binder was used, consisting

of cement and polymers at a ratio of about 8:1 by weight. The water: binder ratio in the mortar was 0.23:1 by weight, resulting in plastic consistency and good workability. Fig. 5 illustrates the two types of carbon fiber reinforcement used.

Each anchor comprised a tow of carbon fibers of the same type used in the unidirectional sheets. The total length of anchors was 600 mm and their weight was 56 g/m, 121 g/m and 228 g/m for anchors with nominal diameters equal to 6.25 mm, 9.25 mm and 12.7 mm, respectively. The rational design for the amount of anchor fibers requires their weight to be equal to or greater than the weight of the EB vertical fibers, as can be expressed by Eq. (1). The cross sectional area, namely the anchor nominal diameter, is then calculated from the weight using Eq. (2):

$$w_{anch} = \gamma w_{f,vert} \quad (1)$$

$$A_{anc} = \frac{w_{anch}}{\rho h} \quad (2)$$

where w_{anch} is the anchor weight; γ is a factor relating the weight of EB vertical fiber to the anchor fiber. Vrettos et al. [33] used γ equal to 1.5, however in the current study the amount of EB vertical fibers were slightly in excess than the anchor fibers to ensure that rupture of anchors would come before. Finally, A_{anch} , ρ and h are the anchor cross sectional area, anchor material density and the height of the anchor, respectively. Values of tensile strength and elastic modulus for the epoxy-impregnated anchors were taken from the manufacturer's data sheets equal to 986 MPa and 95.8 GPa, respectively, corresponding to a thickness of 1 mm.

The test set-up illustrated in Fig. 2a was specially designed and developed for the current study. This set-up enables pure tensile forces to be developed to the anchor-sheet system. The tensile force was applied through steel bars protruding from the column specimen and base block, respectively, as can be seen from Fig. 2. The response of specimens in direct tension was obtained through monotonically applying displacement at a rate of 3 mm/min, using a 250 kN MTS tension-compression testing machine. Loads were measured using a load cell, and displacements were obtained from the crosshead MTS internal transducer and using external linear variable differential transducers (LVDTs) mounted on two opposite sides at a gauge length of 170 mm at the center line of column-base block interface. The instrumentation also comprised strain gauges which were mounted on the pre-impregnated dowel component of each anchor, at a distance of 20 mm from the column-base block cross section as illustrated in Fig. 4c.

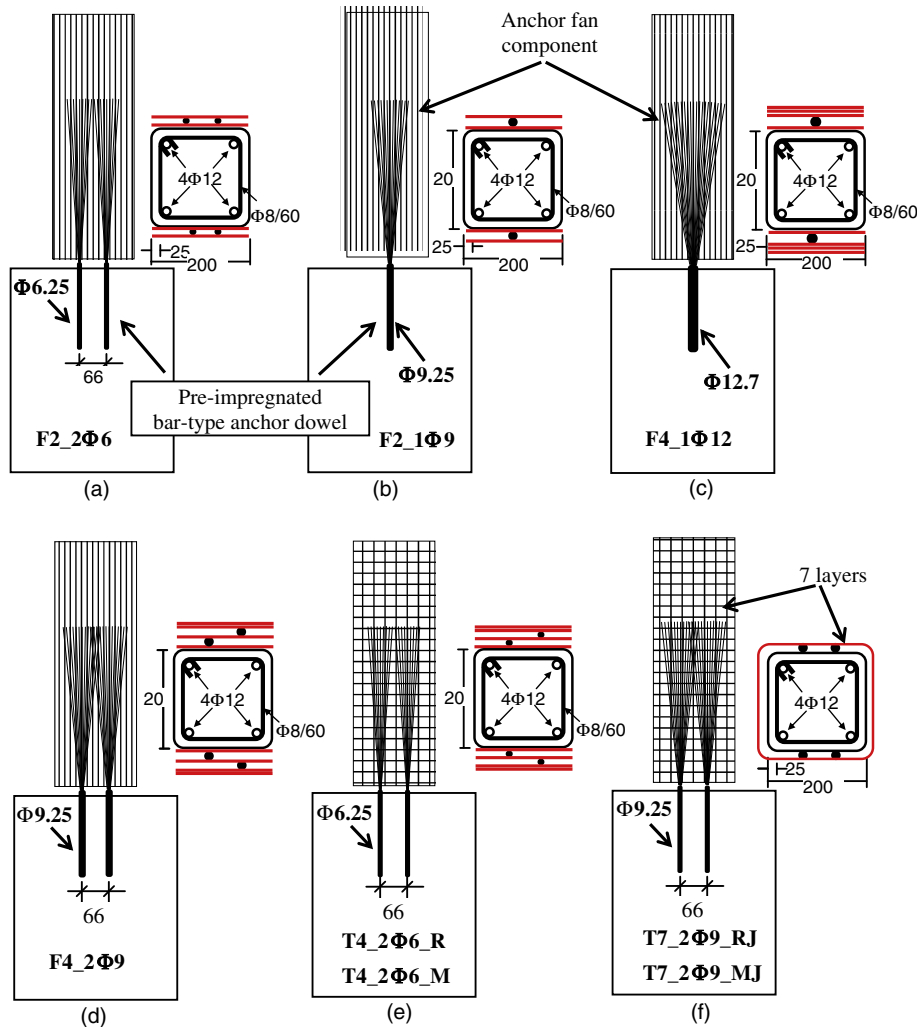


Fig. 3. The eight specimens tested.

3. Experimental results and discussion

The response of all specimens tested is given in Fig. 6 in the form of load–displacement curves. Key results are presented in Table 2. They include: (1) The peak force. (2) The displacement corresponding to peak force. (3) The average tensile capacity of each anchor in terms of force and stress, respectively. (4) The maximum average anchor tensile strain at the column–footing interface, which is defined as anchor effective strain ($\epsilon_{anc,eff}$). The strain values are: (i) calculated on the basis of the anchor nominal diameter and elastic modulus for the epoxy-impregnated anchors and (ii) measured by strain gauges. In addition, the percentage of anchor activation, expressed by the ratio, $\epsilon_{anc,eff}/\epsilon_{fu}$, is also presented. Note that the anchor ultimate uniaxial tensile strain $\epsilon_{fu} = f_{fu}/E_f$, derived by using tensile strength (f_{fu}) and elastic modulus (E_f) values presented in previous section, was 1%.

3.1. Specimens strengthened with FRP anchors- FRP unidirectional sheets

Fig. 7 illustrates the response of each individual specimen strengthened with FRP anchors- FRP unidirectional sheets in the form of load–displacement plots. The performance and failure mode of all specimens (F2_2Φ6; F2_1Φ9; F4_4Φ12; F4_2Φ9) was controlled by tensile rupture of the carbon spike at the col-

umn-base block interface, as shown in Fig. 8. This was an important requirement, as the main objective in this study was to evaluate the effectiveness of FRP anchors in connecting FRP sheets to concrete. The average tensile capacity of the anchors, calculated by dividing the total force by the total number of anchors, was equal to 19.24 kN, 48.55 kN, and 67.92 kN for the carbon spike anchors with nominal diameters of 6.25 mm, 9.25 mm and 12.7 mm, respectively. The corresponding values for the effective strain corresponding to anchor tensile rupture were 0.0066, 0.0075 and 0.006. With only the exception of specimen F2_2Φ6, where all (four) anchors ruptured simultaneously, in the rest specimens the anchors ruptured successively in two stages, namely in each side of the column, as it can be very clearly observed in Fig. 7b–d.

3.2. Specimens strengthened with FRP anchors- textile bidirectional fibers

Fig. 9 presents the load–displacement response curves of each individual specimen where FRP anchors were used in connecting bidirectional textile sheets to concrete. For the specimens that the textile sheets were bonded on the column sides via epoxy resin (T4_2Φ6_R; T7_2Φ9_RJ), the performance and failure mode was again tensile rupture of the anchors. However the effectiveness of this system was reduced due to the lower continuity between

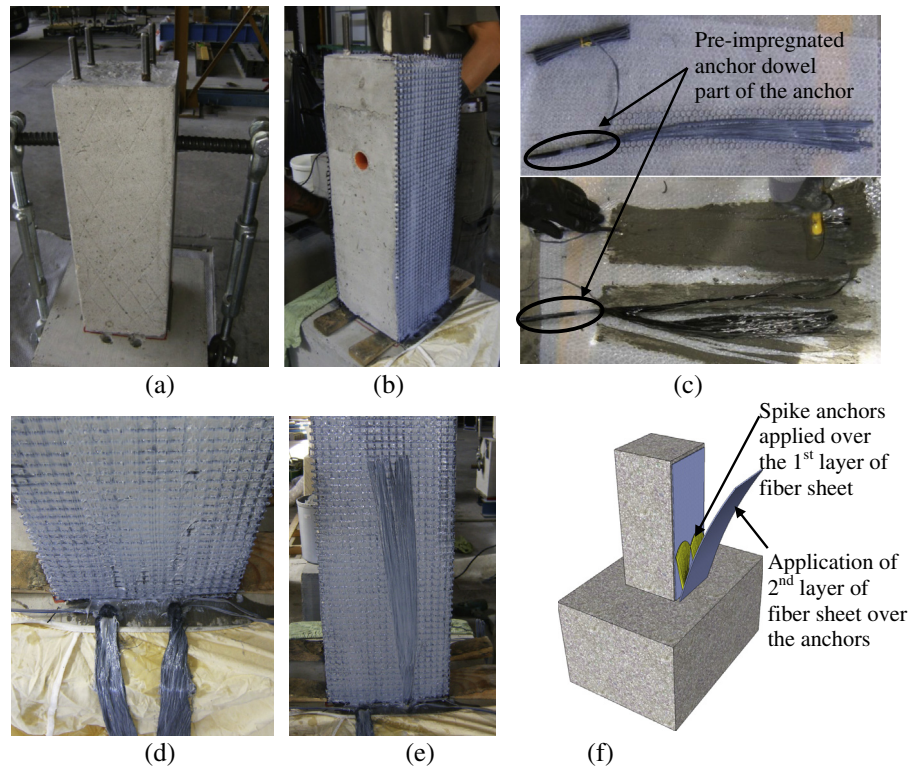


Fig. 4. (a) Properly prepared specimen before strengthening. (b) Bonding of the EB (unidirectional or textile) carbon fiber sheets. (c) Impregnation of the bundles of the fan anchor component with epoxy resin and mortar. (d) Placement of the carbon fiber anchor into the concrete holes. (e) Fanning out of fibers over the carbon fiber textile. (f) Application of the last carbon fiber sheet.

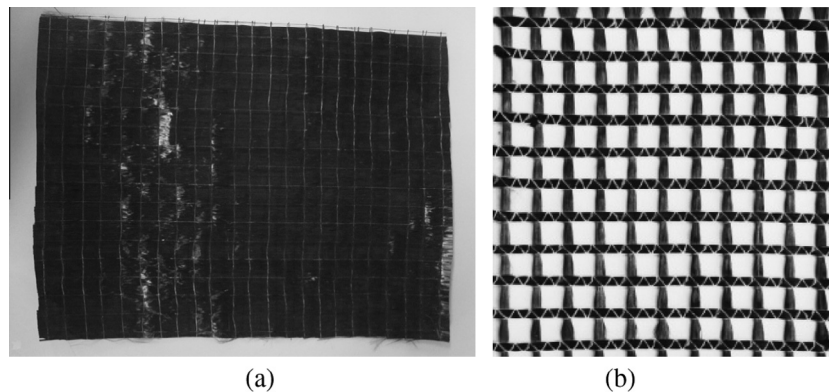


Fig. 5. Carbon fiber: (a) unidirectional sheet and (b) bidirectional textile.

the anchor protruding fibers and the vertical fibers of the textile. This resulted in lower activation of the connection system and consequently in partial rupture of the better connected anchor fibers. This concept is illustrated very well in Fig. 9c, where the successive vertical drops in resistance indicates individual fracturing of bundles of anchor's fibers. Therefore, the average tensile capacity of the anchors was lower, namely equal to 11.17 kN and 17.50 kN for the carbon spike anchors with nominal diameters of 6.25 mm and 9.25 mm, respectively.

For the specimens that the textile sheets were bonded on the column sides with mortar (T4_2Φ6_M; T7_2Φ9_MJ), the performance and failure mode was governed by debonding and slip of the anchors from the textile, as can be very illustratively seen in Fig. 10. The premature debonding of the spike anchors has considerably limited the effectiveness of this connection system. As a

result, the average tensile capacity of the anchors was further reduced to 9.59 kN and 14.60 kN for the anchors with nominal diameters of 6.25 mm and 9.25 mm, respectively. An important aspect of the response of specimens T4_2Φ6_M and T7_2Φ9_MJ (Fig. 9b and d) is that, contrary to epoxy-impregnated, the mortar-impregnated textiles did not fail abruptly since debonding (when the mortar tensile capacity was reached) and slip of the anchor fiber bundles propagated rather slowly, resulting in higher deformation at failure compared with FRP, especially in the presence of TRM confinement (Fig. 9d).

4. Discussion

All specimens responded as designed and failed by the carbon spike anchors failure (rupture or debonding). In terms of the

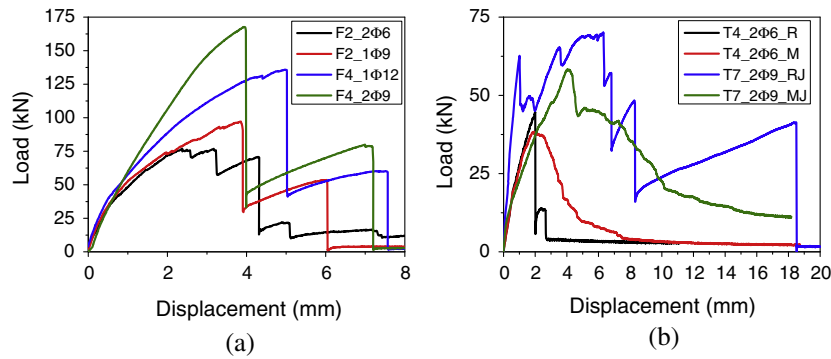


Fig. 6. Load versus displacement curves for tested specimens with: (a) anchor-FRP and (b) anchor-textile systems.

Table 2
Summary of test results.

Specimen notation	(1) Peak force (kN)	(2) Displacement at peak force (mm)	(3) Tensile capacity of each anchor		(4) Tensile strain of the FRP Anchor, (-)			(5) Failure Mode
			Force, (kN)	Stress, $f_{anc,eff}$ (MPa)	(i) Calculated, $f_{anc,eff}/E_f$	(ii) Measured with SGs	$\epsilon_{anc,eff}/\epsilon_{fu}$	
F2_2Φ6	79.97	3.18	19.24	627	0.0066	Unreliable recordings	0.66	Anchors rupture
F2_1Φ9	97.12	3.85	48.55	722	0.0075	0.00445	0.75	Anchors rupture
F4_1Φ12	135.83	4.99	67.92	535	0.0060	0.0073	0.60	Anchors rupture
F4_2Φ9	167.7	3.97	41.93	623	0.0065	0.0053	0.65	Anchors rupture
T4_2Φ6_R	44.67	2.00	11.17	365	0.0038	Unreliable recordings	0.37	Anchors rupture
T4_2Φ6_M	38.36	1.25	9.59	313	0.0032	0.0038	0.32	Debonding and slip of anchors from the textile
T7_2Φ9_RJ	70.1	6.20	17.51	260	0.0027	0.0034	0.27	Rupture of the anchors one by one successively
T7_2Φ9_MJ	58.3	4.02	14.60	217	0.0023	0.0022	0.23	Debonding and slip of anchors from the textile

various factors investigated in this experimental program, an examination of the results (Table 2) in terms of tensile anchor capacity, anchor effective strain and failure modes, revealed the following information.

Effective strain of fiber anchor. Of crucial importance in the design of an FRP-based strengthening system is the so-called “effective strain”, defined here as the average tensile strain in the fiber anchors at failure. Experimental evidence [27,33] suggests that even if failure of the FRP anchors is due to tensile rupture, this failure strain is, in general, less than the uniaxial ultimate strain derived from material testing. The anchor effective strain was calculated herein on the basis of the anchor nominal diameter and elastic modulus for the epoxy-impregnated anchors in the base blocks’ holes (Table 2). For the specimens strengthened with FRP systems, the average effective strain of the anchors was 0.0067. However, for the specimens strengthened with textile-based reinforcement, the effective strain was significantly reduced to 0.0033 and 0.0027 for resin (T4_2Φ6_R; T7_2Φ9_RJ) and mortar (T4_2Φ6_M; T7_2Φ9_MJ) impregnated textiles, respectively. It should be also mentioned here that the anchor effective strain depends strongly on the nature of loading (monotonic or cyclic). The effective strain of the anchors tested by [33], in an identical anchor – FRP system, was 0.0047, namely 30% lower than the strain measured here, due to the effect of the reversed cyclic loading on the anchors failure mode.

Number of Anchors (Specimen F2_2Φ6 versus F2_1Φ9; Specimen F4_2Φ9 versus F4_1Φ12). Whereas using one 9.25 mm diameter anchor (per column side) was 15% more effective than two 6.25 mm diameter anchors in connecting two FRP carbon sheets to concrete, the use of one large anchor ($\Phi 12.7$) was 14% less effective in connecting four FRP carbon sheets than two 9.25 mm diam-

eter bars did. Therefore, no clear conclusion can be made about the preferable number of anchors, with approximately the same cross sectional area, in connecting a certain amount of EB FRP sheets to concrete.

Anchors cross-sectional area (Specimen F2_2Φ6 versus Specimen F4_1Φ12; Specimen F2_1Φ9 versus F2_2Φ9; Specimen T4_2Φ6_R versus T7_2Φ9_RJ; Specimen T4_2Φ6_M versus T7_2Φ9_MJ). Doubling the cross-sectional area of spike anchors, connected to FRP sheets, resulted in increases of the tensile capacity of 70% (F2_2Φ6 versus F4_1Φ12) and 73% (F2_1Φ9 versus F2_2Φ9). Additionally, the heavier anchors were slightly less effective by about 10% in terms average effective strain at failure. For the anchor-textile systems impregnated both with epoxy resin and mortar, the corresponding increase of the system’s tensile capacity was approximately 50%, whereas the decrease in the heavier anchors’ average effective strain was much higher, namely 30%.

Effectiveness of the anchors in FRP versus textile based systems (Specimen F2_2Φ6 versus T4_2Φ6_R; Specimen F4_2Φ9 versus T7_2Φ9_RJ). Despite the equal amount of vertical carbon fibers used in the unidirectional sheets and bidirectional textiles (bonded on the column sides), the anchors effectiveness in the latter case was roughly the half (Table 2). In terms of anchor effective strain, the average value was reduced to 0.0032 for connecting textile-based systems from 0.0065 calculated for FRP ones. This is thought to be due to the lower continuity between the anchor protruding fibers and the vertical fibers of the textile.

Epoxy resin versus mortar in anchor-textile systems (Specimen T4_2Φ6_R versus T4_2Φ6_M; Specimen T7_2Φ9_RJ versus T7_2Φ9_MJ). When FRP spike anchors are used in connecting EB bidirectional textile reinforcement to concrete, epoxy resin is more

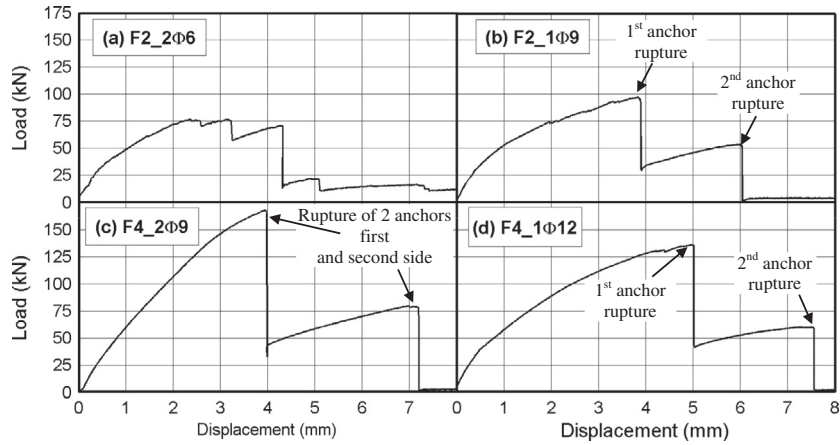


Fig. 7. Load versus displacement response curves for each individual specimen in which FRP anchors are connecting FRP unidirectional sheets to concrete.

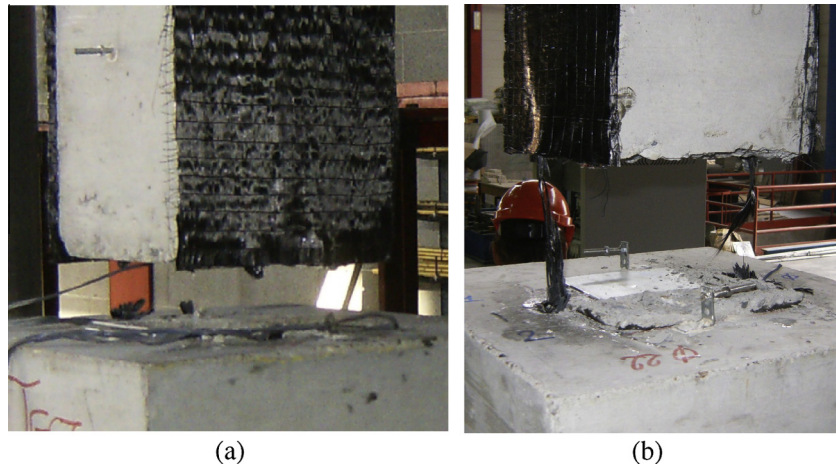


Fig. 8. Tensile rupture failure of the carbon spike anchors in specimens: (a) F2_4Φ6 and (b) F4_1Φ12.

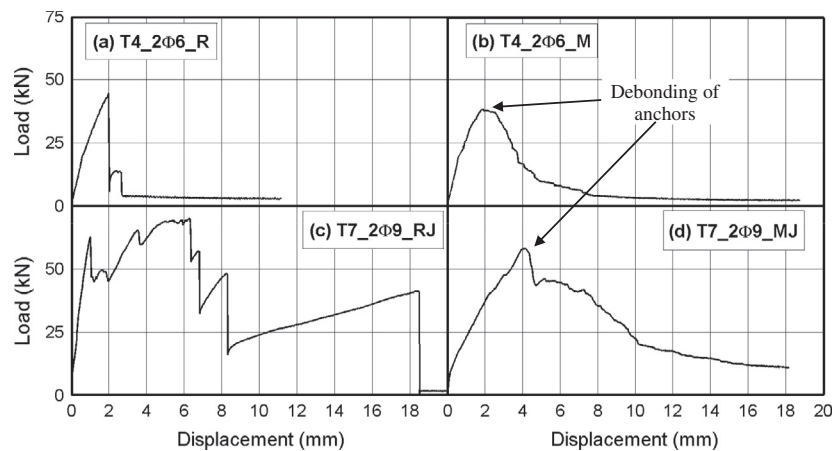


Fig. 9. Load versus displacement response curves for each individual specimen in which FRP anchors are connecting carbon bidirectional textile sheets to concrete.

effective bonding agent than mortar. For the specimens where mortar (T4_2Φ6_M; T7_2Φ9_MJ) was used instead of resin (T4_2Φ6_R; T7_2Φ9_RJ) at the anchor-textile interface, the system's tensile capacity dropped 15%. This is attributed to the lower tensile strength of mortar (specimens T4_2Φ6_M and T7_2Φ9_MJ),

which resulted in debonding and slip of anchors from the textile, whereas for the anchors bonded on the textile reinforcement with resin, the failure was always controlled by anchor rupture. It is noted here that the pre-impregnated anchor dowel component was in all cases inserted in epoxy filled holes.

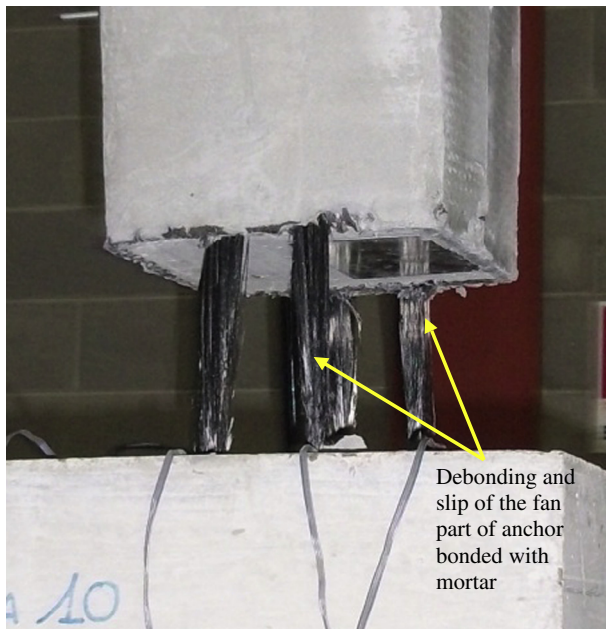


Fig. 10. Debonding and slip failure of the carbon spike anchors bonded with mortar on a TRM jacket (specimen T7_2Φ9_MJ).

5. Conclusions

In the present study the authors investigated the effectiveness of carbon fiber spike anchors in connecting FRP and TRM sheets to concrete surfaces by investigating a series of parameters. These parameters comprise the weight and number of anchors, the bonding agent used to bind the sheet-anchor system and the presence of external confinement. A careful interpretation of the experimental results leads to more specific conclusions which are summarized in a rather qualitative manner as follows:

- The carbon fiber spike anchors comprise an effective anchorage system in preventing premature delamination of FRP and TRM sheets from concrete surfaces. When they are properly anchored into concrete and connected to EB FRP sheets, the spike anchors fail due to tensile rupture.
- Doubling the amount of spike anchors results in increasing the anchors-FRP tensile capacity by 70%, however the corresponding increase is only 50%, when the same anchors are used to connect TRM sheets to concrete.
- The effectiveness of FRP spike anchors in connecting EB FRP uniaxial sheets to concrete is twice as much than their capacity in connecting EB bidirectional textile fiber sheets. In terms of anchor effective strain, the average value was reduced to 0.0032 for connecting textile-based systems from 0.0065 calculated for FRP ones.
- The effectiveness of FRP spike anchors in connecting EB bidirectional textile reinforcement to concrete is slightly lower (by about 15%) when mortar is used as bonding agent instead of epoxy resin, and also failure is controlled by anchor debonding rather than anchor rupture.
- Even if failure of the FRP anchors is due to tensile rupture, this failure strain is, in general, less than the uniaxial ultimate strain derived from material testing. For the specimens strengthened with FRP systems, the average effective strain of the anchors was 0.0067, while for the specimens strengthened with textile-based reinforcement, the effective strain was significantly reduced to 0.0033 and 0.0027 for resin and mortar impregnated textiles, respectively.

Despite their relatively limited number, all test results presented in this study indicate that carbon fiber spike anchors is a promising solution to prevent or delay delamination of EB FRP or TRM systems. However, it is noted that due to the limited number of test results and the fact that the execution (preparation and application) of this anchorage system has no quality control or certification for the time being, the conclusions should be used with care. Future research should be directed towards providing a better understanding of the parameters investigated in this study.

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