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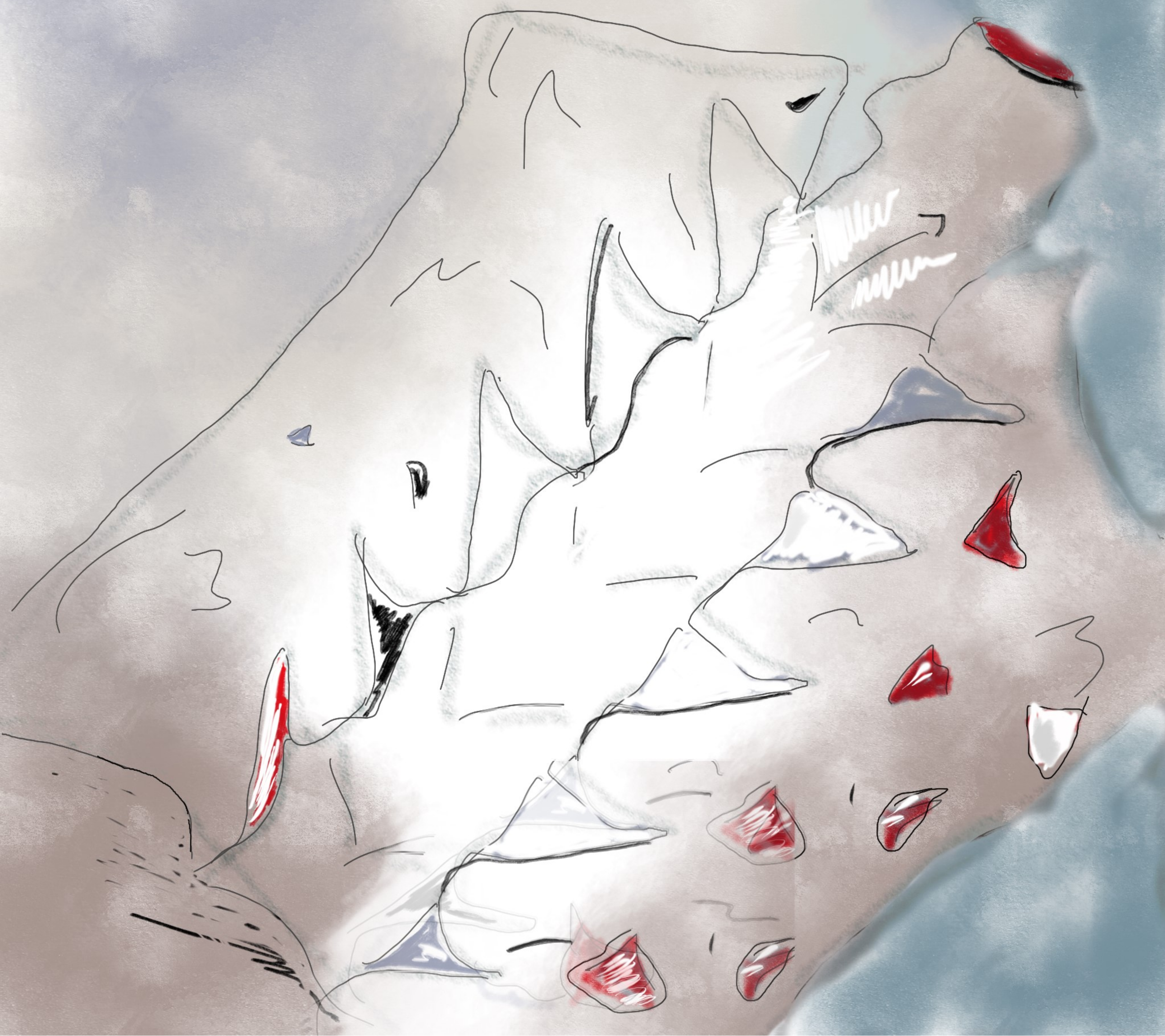

Effect of confinement on the behavior of FRP straight anchors

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ABSTRACT

The use of Fiber Reinforced Polymer (FRP) materials in combination with the Externally Bonded Reinforcement (EBR) method is a strengthening system (EBR-FRP system) that is commonly deployed to increase the load carrying and/or ductility capacity of structural members. One of the main drawbacks of EBR-FRP systems is premature debonding, which entails the debonding of the FRP reinforcement from the substrate at a strain level that is typically a small fraction of the rupture strain. In order to prevent or delay premature debonding, FRP anchors have proven to be a suitable solution to prevent the delamination of FRP materials from the concrete substrate when the Externally Bonded Reinforcement (EBR) method is used by ensuring continuity of the load path from the FRP sheets into the structure or improving the FRP-to-concrete bond strength. On the other hands, one of the phenomena that could affect the behavior of FRP anchors is the concrete confinement. Hence, the research here presented aims to comparing test results for a single FRP anchor in confined and unconfined configurations to establish a ratio between the confined and the unconfined bond strengths. Subsequently, Results are discussed and compared with theorical studies.

1 INTRODUCTION

The use of Fiber Reinforced Polymer (FRP) materials in combination with the Externally Bonded Reinforcement (EBR) method is a strengthening system that is usually developed to increase the load-bearing and/or ductility capacity of structural members, with comprehensive overviews of the utilization of FRP that being available in the literature [1–3]. EBR-FRP systems incorporating FRP anchors can be used in masonry structures [4] or in reinforced concrete structures for a wide range of applications such as slabs [5,6], columns [7,8], beam-column connections [9-12], shear walls [13,14].

One of the main disadvantages of EBR-FRP systems is premature debonding of FRP from concrete surface, which causes the debonding of the FRP reinforcement from the substrate at a strain level that is typically a small portion of the rupture strain. Among different solutions to prevent or delay premature debonding, FRP anchors have proven to be an appropriate solution [2,3] to prevent the debonding or delamination of FRP materials from the concrete substrate when the Externally Bonded Reinforcement (EBR) method is used, by ensuring continuity of the load path from the FRP sheets into the structure or improving the FRP-to-concrete bond strength.

FRP anchors consist of a bundle of fibers, or a rolled fiber sheet together (Figure 1) which impregnated with epoxy resin as adhesive and with one end inserted into a hole pre-drilled in the structure member and the other end bonded to the FRP sheet.

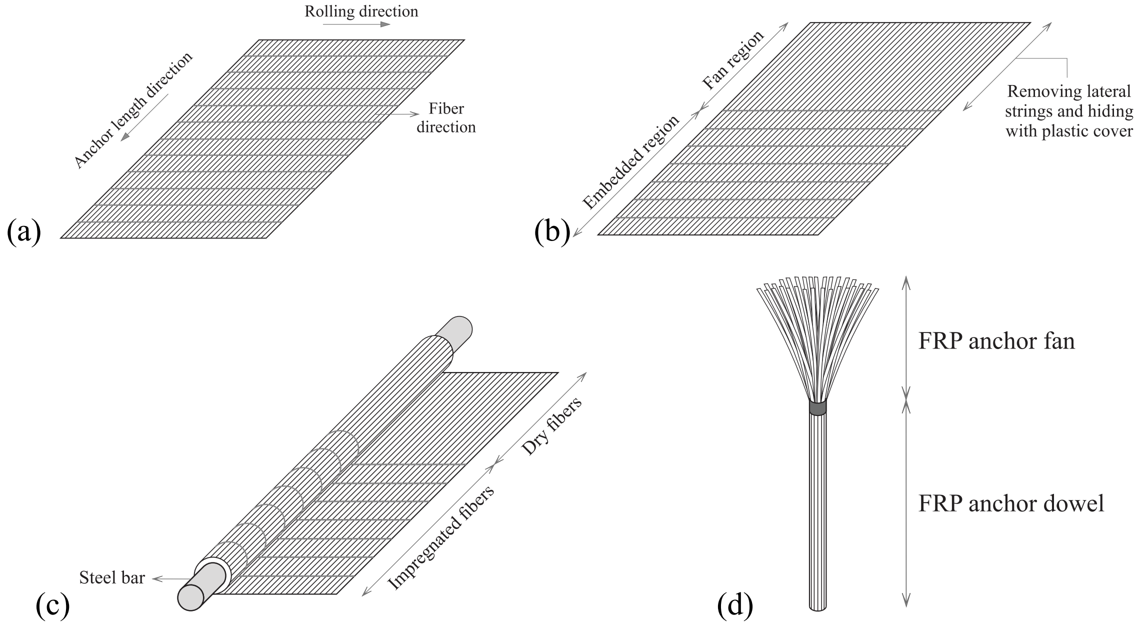


Figure 1: The process of construction of FRP anchor, (a) Cutting FRP sheet in desired dimension, (b) Removing lateral string in Fan region, (c) Impregnating both sides of FRP sheet in dowel region and rolling by a slender steel bar, (d) Removing steel bar and opening fibers in Fan region

Anchors are generally divided into bent and straight anchors, depending on the orientation in which the anchors are introduced into the structure. FRP anchors can be utilized in two different locations with respect to the FRP sheet, either within the boundaries or at the end of the FRP sheet. For situations that the anchors are installed within the boundaries of the FRP sheet, the anchors increase the load that is essential to debond the FRP sheet from the concrete surface by reducing the slip of the FRP at the anchor. To be specific, the anchor cannot transfer the entire force that it can carry to the FRP reinforcement completely. In addition, the FRP anchors installed within the boundary of an FRP string bonded to member surface reduce crack growth and make delayed debonding occur in a time greater than the service life. Several studies have investigated the behavior of FRP anchors when the anchors modify the boundary condition of the differential equations of the bond. The exact theoretical behavior for FRP used in masonry is explained in the literature [4,15]. A different behavior occurs when the FRP anchor is installed at the end of the FRP sheet, as illustrated in Figure 2. In this case the FRP sheet completely debonds before the FRP anchor is activated, and the load from the FRP sheet is totally transferred through the anchors to the concrete substrate only when the FRP reinforcement is detached from the surface. This second situation, in which the anchors are located at the end of the sheet, is the case under study herein. For this situation, some analytical models have been presented to quantify the pullout strength of straight FRP anchors [16]. Castillo [17] after studying previous investigations of different researchers concluded that the efficiency of bent anchors is significantly lower than straight anchors, due to the fibers being less well aligned with the direction of the applied force.

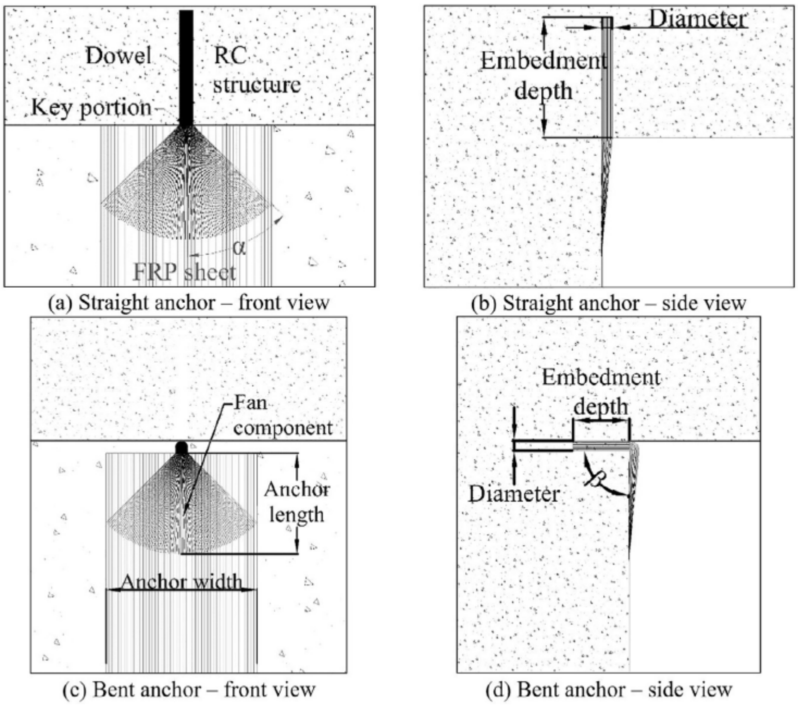


Figure 2: Attributes of FRP anchors [18]

Straight anchors are typically used at the end of the FRP sheet to transfer the forces from the sheet into the structural element, ensuring load path continuity. One of the practical uses of straight FRP anchors is in strengthening RC columns. Two different seismic FRP-EBR strengthening schemes for RC columns have been identified in the literature, with one scheme intended to improve shear behavior and/or the confinement of the column and the other designed to increase flexural strength at the column-base joint (Figure 3). The use of FRP anchors in the first scenario is necessary only when a physical obstruction exists (typically a wall, which creates a gap in the FRP confinement as shown in Figure 3) and increases the drift capacity of the columns when compared to the as-built columns [19]. The second scenario requires the use of FRP anchors to transfer forces from the vertical FRP sheets on the columns to the RC base and reduces the drift up to the moment when the anchors fail, which corresponds with the peak load.

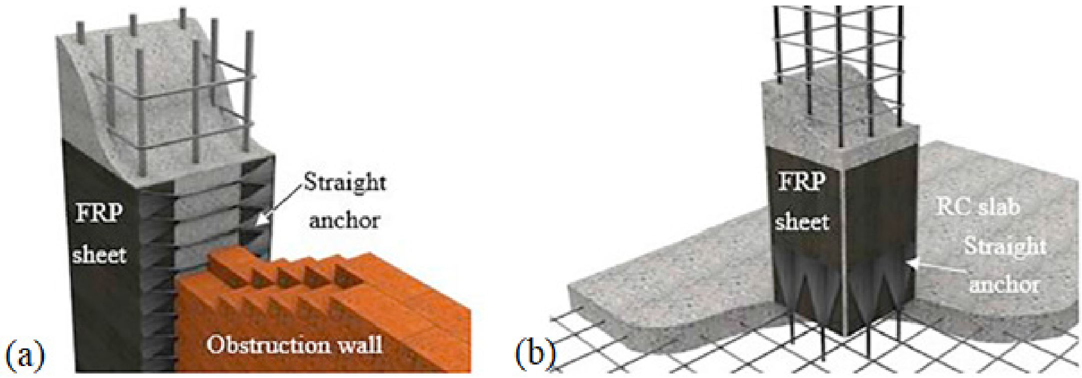


Figure 3: Seismic strengthening of RC columns, a) shear strengthening of a RC column, b) Flexural strengthening of column-base joint [19]

Orton [20] stated that the CFRP can provide continuity through the negative or positive moment reinforcement by being means of a CFRP sheets and anchors applied to the top or bottom surface of the beam in the beam-column connections.

FRP anchors would typically be subjected to a combination of loads from different directions, but as a simplification it has been assumed that the tension load is unidirectionally applied from the FRP sheet that can be seen at the bottom of Figure 2a and c. This approach is in agreement with similar approaches followed profusely in the past [20]. In fact, by pull-out tests, the behavior of straight anchors could be investigated. By using pull-out test, Akyuz and Ozdemir [21,22] indicated that the capacity of a CFRP anchor is directly related to the number of carbon fibers in the sheet. Ozbakkaloglu and Saatcioglu [23] illustrated that Increase in the inclination angle results in a significant reduction in the pullout capacity of the anchors. They also [23,24] identified three failure modes, namely anchor pull-out, a combination of pull-out and concrete cone failure, and fiber rupture in the key portion.

On the other hand, one of the phenomena that could affect the behavior of FRP anchors is the concrete confinement. In a reinforced concrete member, confinement is achieved by the suitable placement of transverse reinforcement. However, ACI 355.4-19 [25] and EAD 330499 [26] both permit the use of confined testing for service-condition tests not only to assess the anchor bond strength to act as a reference when establish anchor robustness with respect to e.g. temperature, creep, installation, but also to establish a reference value to be adopted in design when dealing with the so-called combined pull-out and concrete cone failure mode [27, 28].

Similarly, in the present study, the bond strength and the failure modes of FRP anchors are established by comparing confined and unconfined conditions when varying anchor embedment depth.

2 METHOLOGY AND EXPERIMENTAL PROGRAM

2.1 Materials used and their properties

Unidirectional carbon fiber (CFRP) sheets with a nominal design thickness of 0.17 mm were employed for preparing FRP anchors. On the other hand, the epoxy resin Sikadur-330 was employed as the matrix phase of the CFRP composites. Based on the ambient temperature (23 °C) and according to the producer's data sheet, the resin of the strengthened specimens was cured for 7 days before testing. The properties of the fibers [29] and of the resin [30] according to the manufacturer's data sheet are presented in Table 1.

Table 1: Mechanical properties of Material according to the manufacturer's data sheet.

Material	Type	Modulus of elasticity (GPa)	Ultimate tensile strength (MPa)	Thickness (mm)	Ultimate tensile strain (%)
Fibers	Sika Wrap-300C [29]	230	4000	0.17	1.7
Resin	Sikadur-330 [30]	4.5	30	-	0.9

2.2 Preparing FRP anchors

The anchors were fabricated by cutting a desired sized rectangular piece from the FRP sheet. The anchors were then formed by applying epoxy to both sides of the FRP piece and then rolling the sheet into a cylinder. Applying epoxy to the FRP before rolling it ensured full impregnation of the anchor (Figure 4a to 4d). It should be noted that the prepared FRP anchors had nominal diameters (when impregnated and dried) averagely 16 mm for the sheet with width of 150 mm. for applying the load to FRP anchors, some threaded rods with the diameter of 32mm and the length of 100 mm were selected as a sleeve and a hole inside with the diameter of 20 mm that was drilled through length of threaded rod. Then, the rolled FRP sheet inserted into the drilled hole in threaded rod (Figure 4e). It should be noted the created hole had a smooth and prismatic section in the primary tests. But, after observing bond failure in the sleeve, in the following tests, the internal hole in the threaded rods were threaded.

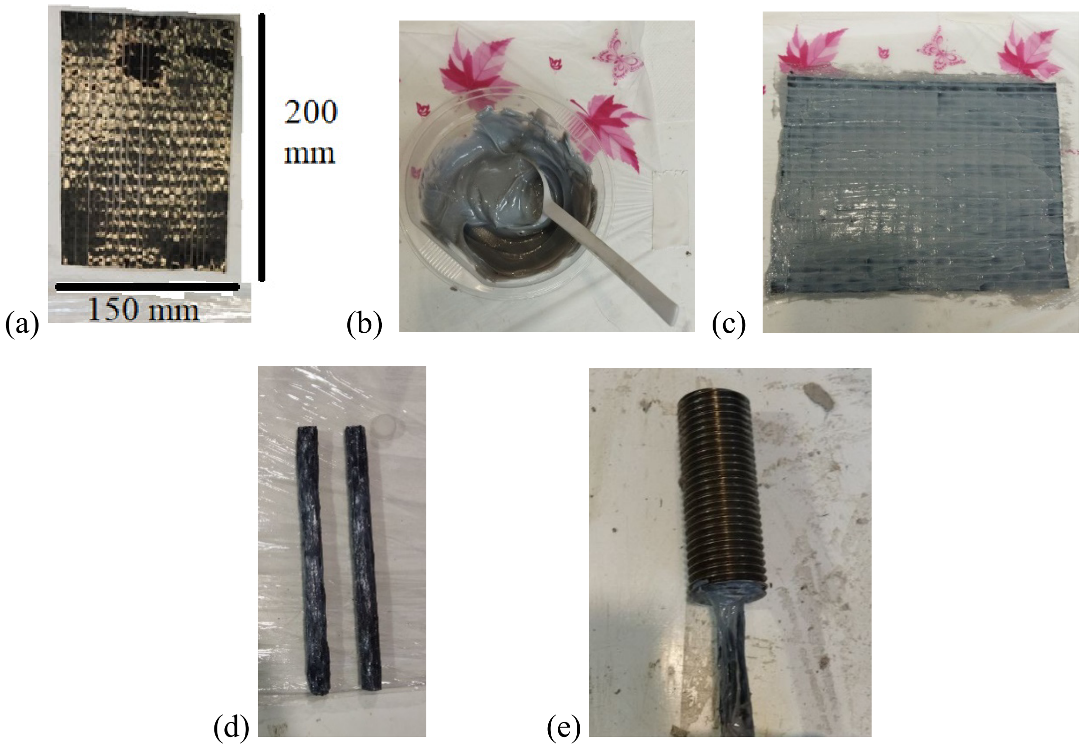


Figure 4: Preparing FRP anchors, a) Cutting a desired sized rectangular piece from the FRP sheet, b) Preparing epoxy resin, c) Adding epoxy resin to both sides of FRP piece, d) Rolling the epoxy added FRP pieces into a cylinder shape, e) Inserting FRP anchor into threaded rod as sleeve for applying the load

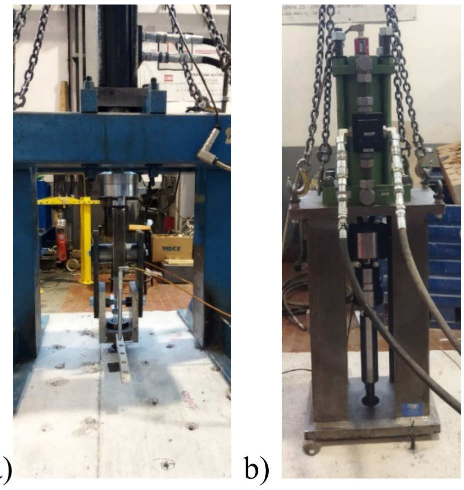
2.3 Installation FRP anchors on concrete slab

FRP anchors were installed in reinforced concrete slabs optimized to prevent splitting failure induced by anchor loading. Three RC flat slabs 1550 × 1250 × 250 mm (Figure 5) were casted to investigate the performance of the FRP anchors. Ready-mix concrete of class C20-25 was used for casting the slabs. The average compressive strength of concrete for each slab, $f_{c,cube}$, measured by compressive testing 150 mm concrete cubes on the day of the test, is given in Table 2. The installation sequence started with hole drilling to the required embedment length (50 mm or 75 mm) and with the specified diameter (20 mm). Consequently, prior to inserting the anchor, the holes were filled with the resin.

Figure 5: Inserting FRP anchors into pre-drilled hole in the concrete slab.

2.4 Test Setup

Two different test apparati were adopted for confined and unconfined configurations. In "confined tests", a steel square plate was placed at the bottom of the reaction frame provides the confinement (Figure 6b). The diameter of the hole in the confining plate d_c was 35mm and the width of plate was 200 mm. In unconfined tests, the distance between the supports was equal to 635 mm (Figure 6a). All the tests were carried out using closed-loop servohydraulic testing machines with 100 kN load capability for unconfined test and 300 kN for confined tests under displacement control. The displacement rate was 0.02 mm/s. The slip at the loaded end was monitored by two 100 mm LVDTs placed symmetrically at the two sides of the threaded rod. All data were acquired with an HBM Spider8 data acquisition system.



a) b)

Figure 6: Test apparati for pull-out test, a) Unconfined conditions, b) Confined conditions

2.5 Test parameter and test code description

Table 2 reports test parameters and relevant code for all the tests. The test code is composed as it follows: C**XX**W**YYY**L**ZZ**-**Abc**-**n**, where XX is the concrete compressive strength, YYY is the FRP strip width, ZZ is the actual embedment depth, Abc indicate the boundary conditions ('Cf' for confined and 'Ucf' for confined) and n indicates the repetition.

Table 2: Specimens descriptions

Test Number*	Specimen label	Concrete Compressive strength (MPa)	FRP strip width (mm)	Actual Embedment Depth (mm)	FRP anchor diameter (mm)	Hole diameter (mm)	Concrete Confinement condition
1	C25W150L50-Ucf-1	31	150	51	16	20	Unconfined
2	C25W150L50-Ucf-2	27.3	150	50	16	20	Unconfined
3	C25W150L50-Ucf-3	27.3	150	52	16	20	Unconfined
4	C25W150L75-Ucf-1	27.3	150	75	16	20	Unconfined
5	C25W150L75-Ucf-2	27.3	150	77	16	20	Unconfined
6	C25W150L75-Ucf-3	27.3	150	76	16	20	Unconfined
7	C25W150L50-Cf-1	28.8	150	54	16	20	confined
8	C25W150L50-Cf-2	28.8	150	52	16	20	confined
9	C25W150L50-Cf-3	28.8	150	54	16	20	confined
10	C25W150L75-Cf-1	28.8	150	76	16	20	confined
11	C25W150L75-Cf-2	28.8	150	77	16	20	confined
12	C25W150L75-Cf-3	28.8	150	75	16	20	confined

* For all specimens, preparing FRP anchor and inserting it into sleeve and concrete were done simultaneously.

3 RESULTS AND DISCUSSION

Test results, in terms of observed failure mode and tensile capacity, are reported in Table 3 and Table 4, where:

- $F_{u,exp}$ is the experimentally determined pull-out capacity, associated to a specific failure mode,
- τ_u is the average bond strength, evaluated as

$$\tau_u = F_{u,exp}/(\pi \cdot d_a \cdot h_{ef}) \qquad (1)$$

being d_a the anchor diameter and h_{ef} the anchor embedment depth.

Table 3: Result Summary (Unconfined conditions)

Test Number	Specimen Label	$F_{u,exp}$ (kN)	τ_u (MPa)	Failure mode
1	C25W150L50-Ucf-1	28	10.3	Concrete cone failure
2	C25W150L50-Ucf-2	25.8	9.9	Concrete cone failure
3	C25W150L50-Ucf-3	27.2	10	Concrete cone failure
4	C25W150L75-Ucf-1	43.4	11.5	Concrete cone failure

5	C25W150L75-Ucf-2	47.8	12.3	Concrete cone failure
6	C25W150L75-Ucf-3	45.1	11.8	Concrete cone failure

Table 4: Result Summary (Confined conditions)

Test Number	Specimen Label	$F_{u, exp}$ (kN)	τ_u (MPa)	Failure mode
7	C25W150L50-Cf-1	44.1	17.2	Pull-out failure
8	C25W150L50-Cf-2	42	16.7	Pull-out failure
9	C25W150L50-Cf-3	47.6	18.2	Pull-out failure
10	C25W150L75-Cf-1	56.6	-	Sleeve failure*
11	C25W150L75-Cf-2	54.9	-	Sleeve failure*
12	C25W150L75-Cf-3	69.5	18.5	Pull-out failure

* In case of sleeve failure, bond was lost outside of the anchor; consequently, bond strength is not evaluated.

3.1 Failure modes

Typical pictures of FRP anchors at failure are shown in Figure 7 and 8 for the failure modes reported in Tables 3 and 4. It is noticed that:

a. under unconfined testing conditions, a concrete cone starting from the tip of the anchor was always observed (Figure 7);
b. where a bearing pressure was applied to the concrete surface (confined conditions), the FRP anchor completely pulled out from the surrounding concrete, with a failure surface at the anchor/bonding agent interface (Figure 8). In a few cases, the loading sleeve was not efficient in load transferring, failing prior to the anchor itself.

Figure 7: Concrete cone failure (test number 6)

Figure 8: Pull out failure (test number 7, 8 & 9)

3.2 Prediction of anchor capacity

Concrete cone capacity can be estimated according to the CCD method [31], as originally established for post-installed mechanical anchors, assuming a failure surface propagating from the anchor tip towards the concrete surface with an angle of approximately 35° and accounting for size effects on the anchor embedment dependency as:

$$F_{cone,CCD} = 13.5 \cdot h_{ef}^{1.5} \cdot \sqrt{f_{c,cube}} \qquad (2)$$

Where confined conditions are applied, and hence bond failure is induced, a Uniform Bond Model (UBM) can be adopted to both evaluate an embedment-independent bond strength value and to predict anchor capacity for different values of embedment depth, as [32]:

$$F_{pull-out,UBM} = \tau_{UBM} \cdot \pi \cdot d_a \cdot h_{ef} \qquad (3)$$

Figure 9 reports the experimentally determined anchor capacities as a function of the anchor embedment depths, comparing them with the predictions according to Eqs. (2) and (3).

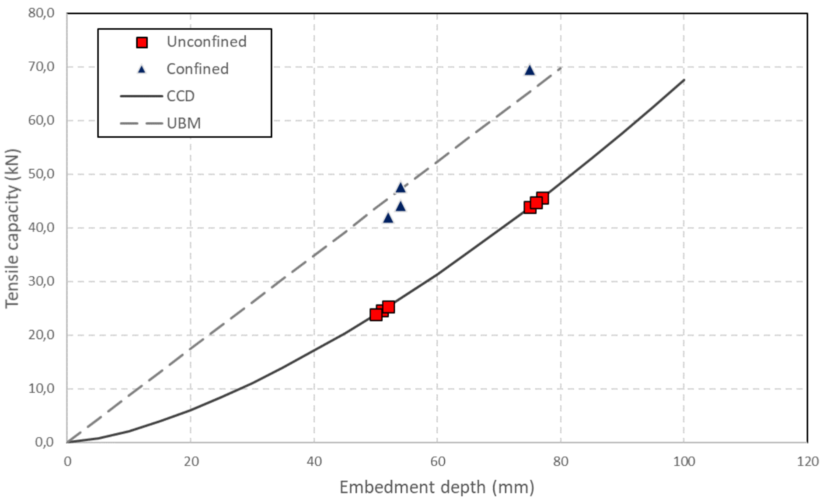


Figure 9: Anchor capacity as a function of the embedment depth, differentiated by testing conditions, and predictions according to the CCD [31] and UBM models [32]

It can be noticed how the CCD is perfectly suitable to estimate anchor capacity in unconfined cases, which is significantly relevant for real applications, where such bond conditions are present. However, under such conditions, only a lower bound estimation of anchor bond strength is possible.

Consequently, assessing the bond strength through confined testing proves efficient in this direction; the UBM fits well the experimental results, returning a mean bond strength value equal to 17.4 MPa. It is remarked that this value, being obtained on the basis of confined conditions testing, cannot be used directly in design, but rather as reference value when other effects are to be assessed, as for instance the influence of temperature, creep, installation conditions. However, should the bond strength obtained through confined conditions be used to predict the capacity associated to a combined pull-out/concrete cone failure mode (as in [28]), the obtained results suggest an unconfined to confined ratio (referred to as α_{setup} in EAD 330499 [26] qualification procedures) equal to 0,5.

4 CONCLUSION

Based on the results of the experimental study and on the comparison with existing models available in literature, the following conclusions can be drawn regarding the behavior of FRP anchors subjected to tensile loading:

- The capacity of FRP anchors can be estimated by pull-out tests in concrete by adapting the same approach currently used for post-installed fasteners in concrete.
- Quality of workmanship has an important role on bond strength of FRP anchors. In fact, poor hole preparation, poor adhesive placement and non-verticality of the anchor (fibers misalignment) may result in remarkable reductions in bond strength of FRP anchors.
- FRP anchors capacity increases with the embedment length. Such increase of FRP anchors, the peak load increases. Such increase is well predicted by a 1.5 exponent power law function of the embedment depth, which is strictly related to the formation, at failure, of a concrete cone starting from the anchor tip.
- When a bearing pressure is applied, and so concrete cone is prevented in favor of a bond failure at the anchor interface, the anchor capacity significantly increases and it can be well estimated by adopting a Uniform Bond Model.

5 ACKNOWLEDGEMENTS

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