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Effect of carbon textile treatment and embedded textile length on textile/matrix interface behaviour from pull-out test

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ABSTRACT: The carbon textile-reinforced concrete (carbon TRC) is an alternative material to strengthen or reinforce the structure in several special environments thanks to its advantages. An important factor influences the mechanical behavior of carbon TRC is the bond strength of the textile/cementitious matrix interface. In order to improve this bond, carbon textile is treated with different products in the manufacturing procedure. This paper presents the results of pull-out tests performed on textile/ matrix interface specimens that were made with two carbon textiles (commercial products with two different fibre treatments), embedded in a concrete matrix with different lengths. As results, all interface specimens gave a typical behaviour as shown in the literature with three phases: perfect bonding phase, debonding phase and pure friction phase. In comparison with the results obtained from pull-out tests on the specimens of the same carbon textile embedded in a concrete matrix with different lengths, it could be found that the maximal force improved about 1.5 times when the embedded length extended 2 times from 2cm to 4cm. However, it's necessary the fracture energy bigger than 4.76 times in order to damage the textile/matrix interface bond in this case. In the other hand, the effect of carbon textile treatment could be found and analyzed. As results, the textile treatment with amorphous silica helped the interface to extend the pure friction phase of its behaviour, while the interface specimens of carbon textile treated with epoxy resin gave a quick failure in the third phase after being reached the maximal force.

Keywords: Textile – reinforced concrete (TRC), textile/matrix interface, pull-out, textile treatment, embedded length.

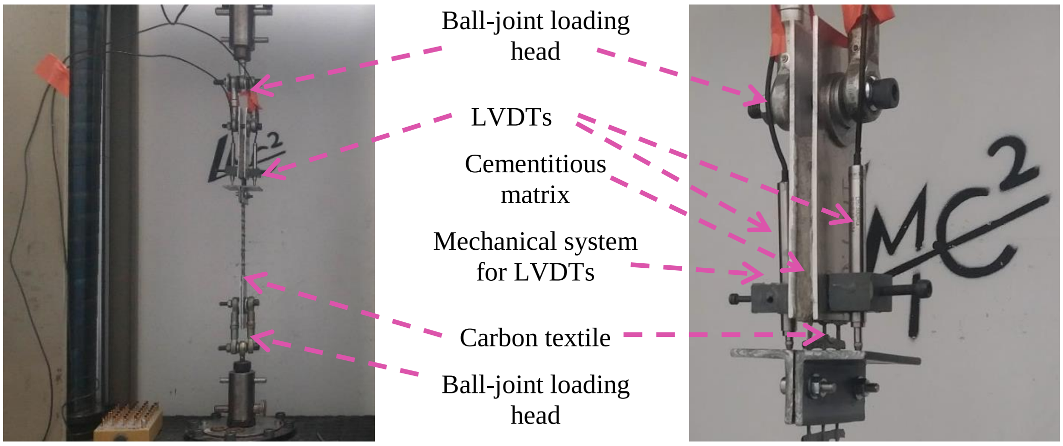
1 INTRODUCTION

The carbon textile-reinforced concrete (carbon TRC) is an alternative material to strengthen or reinforce the structure in some special environments thanks to its advantages. An important factor that influences on the mechanical behavior of carbon TRC is the bond strength of the textile/cementitious matrix interface. With a good adhesion between themselves, it gives the working together with high efficiency between the two materials, which improves greatly the mechanical properties of TRC in the first and second phases of its behaviour. In the literature, there are several methods to characterize the mechanical behaviour of fibre/cementitious matrix interface, Teklal et al (2018). Among these methods, the pull-out test is simple and effective in the laboratory condition. It was successfully used in various studies for fibre/matrix interface response. Almost results showed typical behaviour of fibre/cementitious matrix interface with three phases: perfect bonding phase, debonding phase and pure friction phase. The pull-out behaviour depends on several factors that are coming from the reinforcement fibres such as the fibre nature, the fibre/textile geometric, Ferreira et al (2018), Zhang et al (2013), the fibre treatment, Homoro et al (2019), Lu et al (2018), Ferreira et al (2015), or coming from the cementitious matrix such as matrix nature, phase modification of matrix, Silva et al (2014), Butler et al (2009). Among these factors, the effect of fibre treatment influences strongly on bond strength. Normally, the fibre treatment gives a positive effect to improve the mechanical adhesion (mechanical anchoring), physical adhesion or chemical adhesion. So, the fibre or textile was treated with different products in the manufacturing procedure. To the best of the authors' knowledge, no results are available concerning pull-out tests carried out on carbon textile/cementitious matrix interface specimens. So, in order to understand the interface response in an application of carbon TRC composite, this paper presents the results of pull-out tests performed on carbon textile/ matrix interface specimens. In this study, two carbon textiles (commercial products with two different fibre treatments) were embedded in a concrete matrix with different lengths depending on their geometry. The pull-out specimens were tested by using the tensile machine and measuring chain with two LVDT for a bond slip of interface. Thanks to this test configuration, the "force – slip" curves could be drawn from pull-out tests. In comparison between the results obtained, the effects of textile treatment and embedded length would be found and discussed in this study.

2 EXPERIMENTAL WORKS

2.1 Equipment used

2.1.1 Test machine



(a) (b)

Figure 1: Pull-out test setup; (a): Overview of the test setup; (b) Slip measurement of pull-out test

The test machine (Zwick / Roel 65 kN) was used for the pull-out tests. It has a high force capacity up to 65 kN for the direct tensile or compressive test. In particular, it is also well equipped with a measuring chain that can connect to measuring instruments (with contact measurement methods such as strain gauge or LVDT) to measure deformation or point displacement of the specimen. The tensile load is controlled by the vertical movement of the crosshead thanks to controlling program (Test-Expert II software) in the system computer. During the test, the data, including the mechanical load and the transverse movement of the test machine, are recorded at least twice per second and can then be exported in the form of data sheets for the result analysis. Figure 1a presents the universal traction machine with other equipment for pull-out tests.

2.1.2 LVDT

The LVDTs were used for pull-out tests to measure the relative slip between carbon textiles and cementitious matrix plate when the tensile force increases with time. Two LVDTs were fixed on two surfaces of aluminum plates by a mechanical system. Another system was also fixed on the carbon textile at the position next to the matrix plate. This configuration ensures the negligible deformation of the carbon textile between two mechanical systems. Therefore, the displacement obtained from the LVDTs was a bond slip of pull-out tests. Figure 1b shows the LVDTs configuration for pull-out tests.

2.2 Materials

2.2.1 Carbon textiles

Two continuous carbon textiles used in this experiment are industrial products that were manufactured in a factory in grid form with different grid geometries. These textiles have advantages such as very high tensile strength and Young’s modulus, high corrosion resistance, a low weight per unit area, a simple and flexible application. The two carbon textiles were coated with different treatment products in nature (completely impregnated in epoxy resin for GC1 and with amorphous silica for GC2). The properties of the two studied carbon textiles are summarized in Table 1.

Table 1: Properties of two studied carbon textiles

Properties	GC1	GC2
Ultimate strength (MPa)	2616.6	1311.5
Young’s modulus (GPa)	256.2	143.8
Weight per area (g/m^2)	343	374
Grid geometry (mm × mm)	46 × 41	17 × 17
Type of coating	epoxy resin	silica
Cross-sectional area of one individual strand	1.85 mm^2	1.795 mm^2

2.2.2 Cementitious matrix

This matrix consists of a silico-aluminous-calcium synthetic aggregate obtained by melting (containing about 40% of alumina) which is characterized by a high density and exceptional hardness, as well as a cement consisting essentially of calcium aluminates constituting a binder for refractory applications. The high mono-calcium aluminate content of this cement (about 50%) gives the concrete good mechanical performance. For a small thickness of application, the maximum diameter of the aggregate should be less than 1.25 mm. In particular, a small amount of super-plasticizer and viscosity modifier has been added to the concrete component. The water/cement ratio of this cement matrix was 0.35. The compressive and tensile strengths of the matrix at 28 days are 58.1 MPa and 5.29 MPa while its Young’s modulus is 8.41 GPa.

Table 2. Mixture composition of the cementitious matrix

Composition	
Aggregate (kg/m^3)	1676
Cement (kg/m^3)	669
Superplasticizer (kg/m^3)	4.34
Viscosity modifier agent - VMA (kg/m^3)	0.51
Water (kg/m^3)	234.2
Water/cement ratio	0.35

2.3 *Specimen preparation*

The interface specimens between carbon textiles (GC1 and GC2) and refractory matrix were fabricated at the laboratory condition for pull-out tests (called IN-F.GC1 and IN-F.GC2 in this study). The rectangular plates of a cementitious matrix with dimensions of 100 mm x 300 mm x 10 mm (length x width x thickness) were molded with an anchorage of carbon textiles in it (see figure 2b). The embedded length depends on the geometry of each carbon textile. In this study, it is varied from 3 cm to 5 cm for IN-F.GC1 specimens and from 2 cm to 4 cm for IN-F.GC2 specimens. The placement of the carbon textiles was established in the same way for both pull-out specimens. A transversal yarn (the weft) was placed at the border of the cement matrix plate. Figure 2 below illustrates the preparation procedure of pull-out test specimens.

(a) Preparation step of the cementitious matrix

(b) Molding the specimen plate (IN-F.GC1)

(c) Labeling of the pull-out test specimens (IN-F.GC2)

Figure 2. Preparation procedure of pull-out test specimens

After curing of the cementitious matrix (28 days), each specimen plate was cut (the matrix and as well as the carbon textile), to obtain the specimens with the size of cementitious matrix plate of 100 mm x 65 mm x 10 mm respectively for IN-F.GC1 and 100 mm x 51 mm x 10 mm (length x width x thickness) for IN-F.GC2. Both ends of the test specimens were bonded with aluminum plates to transfer tensile load on the pull-out test specimens. Afterwards, all samples are labeled for the tests (see Figure 2c).

2.4 *Summary of tests*

Table 1 shows the list of specimens for the pull-out tests. There are 21 tests carried out on the interfacial specimens of carbon textiles (GC1 and GC2) embedded in matrix plats with different lengths from 3 cm to 5 cm for GC1 and from 2 cm to 4 cm for GC2.

Table 3. List of tests carried on the pull-out specimens at room temperature

Specimens	Dimensions of matrix block [length x width x thickness (mm^3)]	Embedded length (mm)	Number of tests
IN-F.GC1 – 3cm (a,b,c)	100 x 65 x 10	30	3
IN-F.GC1 – 4cm (a,b,c)		40	3
IN-F.GC1 – 5cm (a,b,c)		50	3
IN-F.GC2 – 2cm (a,b,c)	100 x 51 x 10	20	3
IN-F.GC2 – 2.5cm (a,b,c)		25	3
IN-F.GC2 – 3cm (a,b,c)		30	3
IN-F.GC2 – 4cm (a,b,c)		40	3
Total of tests			21

3 RESULTS

3.1 Idealization of pull-out behavior

Figures 3a, c present all "force - slip" curves obtained from pull-out tests performed on IN-F.GC1 and IN-F.GC2 specimens. As results, it can be found that the pull-out test specimens give the typical behaviours for textile/matrix bond, with two phases for the IN-F.GC1 specimens or three phases for the IN-F.GC2 specimens. Concerning the results on IN-F.GC1 specimens, Figure 3b shows the idealization of its pull-out behaviour with two phases: perfect bonding phase, debonding phase. It couldn't see the pure friction phase in this behaviour because of the effect of the textile treatment with an epoxy resin. The debonding phase can be divided into two small phases: the first with a hardening work and the second with a significant drop. For the idealization, the typical points were used to identify the pull-out behaviour of IN-F.GC1 specimens. The points I, II, II were respectively defined as the beginning of debonding, the total debonding and the rupture of the specimens. The maximum pull-out force is determined by the corresponding force at point II.

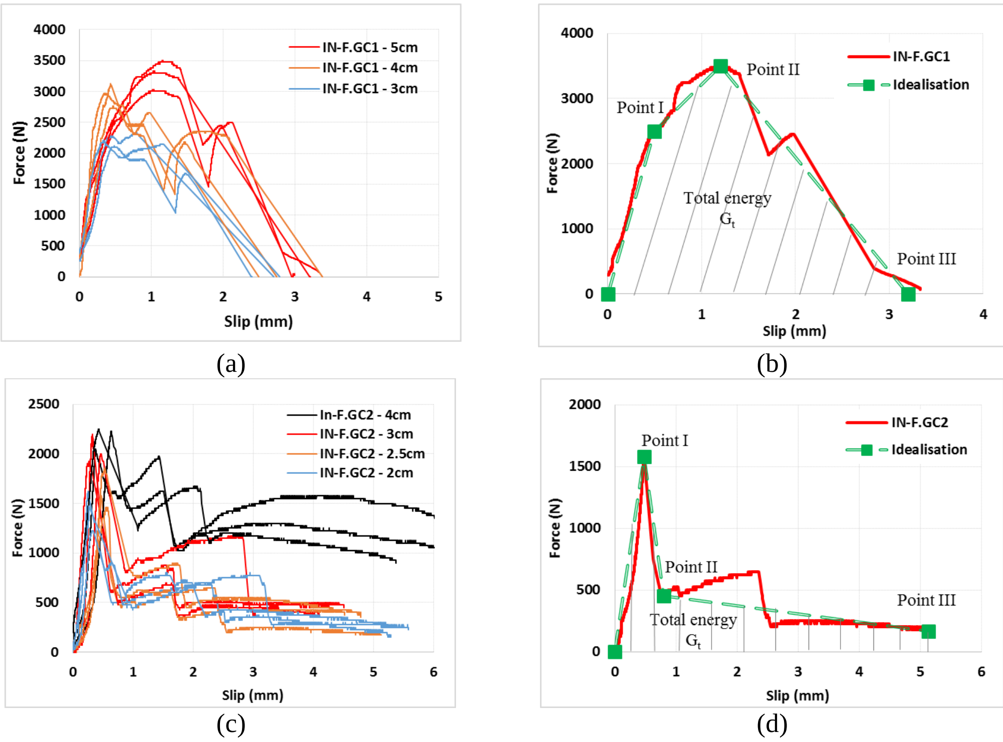


Figure 3. Experimental results of pull-out tests; all "force – slip" curves of IN-F.GC1 (a) and IN-F.GC2 (c); Idealization of the pull-out behaviour: (b) for IN-F.GC1 and (d) for IN-F.GC2

Regarding the idealization of pull-out behaviour for IN-F.GC2 specimens (see Figure 3d), the notation is also used to identify the typical points for the phases of this behaviour. It could be observed that the debonding phase of pull-out behaviour happened quickly. The first micro-cracking and total debonding point seem to be a point (point I). However, the pull-out force then raised a few times in the pure friction phase when it had reached a maximum value at the total debonding point. The friction phase can be divided by two small phases (see Figure 3d): a significant drop in the force (point I-II) and a progressive decrease of pull-out force as a function of the slip (point II-III). The total energy (G_t) to damage the pull-out specimens was identified by the area limited by the "force – slip" curve of its behaviour. The points I, II, III were determined for the same value of total energy between experimental and idealization curves. Figures 3b, d present the idealization of pull-out behaviour for IN-F.GC1 (b) and IN-F.GC2 (d) with the identification of total energy for the pull-out test.

3.2 Results of pull-out tests

3.2.1 For IN-F.GC1 specimens

Table 4 presents all results of pull-out tests performed on IN-F.GC1 specimens. As results, the maximum pull-out force and total energy of IN-F.GC1 increase iss progressively when the embedded length varied from 3 cm to 5 cm. However, all three specimen types gave a similar value of maximum shear stress at the interface between GC1 textile and cementitious matrix.

Table 4. Experimental results obtained from pull-out tests on IN-F.GC1 samples with 3 embedded lengths (3cm, 4cm and 5cm); values in the parentheses ( ) : standard deviation

Specimens	Point I		Point II		Point III		G_t (N.mm)	$\tau_{average}$ (N/mm)
	Force (N)	Slip (mm)	Force (N)	Slip (mm)	Force (N)	Slip (mm)		
IN-F.GC1 - 3cm a,b,c	2031.67 (153.32)	0.328 (0.082)	2221.67 (109.13)	0.966 (0.191)	0.00	2.634 (0.177)	3541.88 (449.82)	74.06 (3.64)
IN-F.GC1 - 4cm a,b,c	2221.67 (194.06)	0.225 (0.026)	2954.17 (182.15)	0.761 (0.076)	0.00	2.932 (0.458)	4857.74 (928.60)	73.85 (4.55)
IN-F.GC1 - 5cm a,b,c	2191.67 (101.04)	0.262 (0.055)	3284.55 (240.97)	1.075 (0.064)	0.00	3.404 (0.128)	6326.98 (262.16)	65.69 (4.82)

3.2.2 For IN-F.GC2 specimens

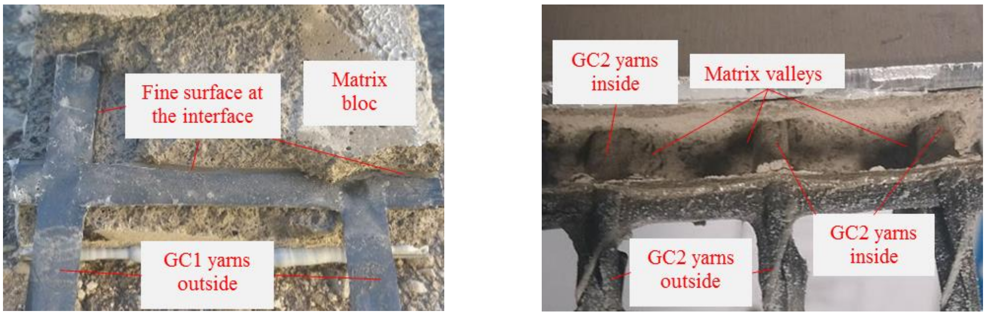
Concerning the results of pull-out tests on IN-F.GC2, the similar tendency of maximum pull-out force, pure friction force and total energy of specimens increase with the increase of embedded length from 2 cm to 4 cm. Table 5 shows all values (force and slip) of the typical points of pull-out behaviour of IN-F.GC2.

Table 5. Experimental results obtained from pull-out tests on IN-F.GC2 samples 4 different embedded lengths (2cm, 2.5cm, 3cm and 4cm); values in the parentheses ( ) : standard deviation

Specimens	Point I		Point II		Point III		G_t (N.mm)	$\tau_{average}$ (N/mm)
	Force (N)	Slip (mm)	Force (N)	Slip (mm)	Force (N)	Slip (mm)		
IN-F.GC2 - 2cm (a,b,c)	1429.79 (196.55)	0.281 (0.037)	579.89 (16.32)	0.761 (0.115)	198.87 (35.95)	5.367 (0.184)	1554.06 (104.34)	79.69 (9.83)
IN-F.GC2 – 2.5cm (a,b,c)	1609.71 (211.57)	0.519 (0.042)	549.20 (106.40)	0.865 (0.166)	295.50 (114.90)	4.813 (0.306)	2018.28 (458.71)	63.33 (8.46)
IN-F.GC2 - 3cm (a,b,c)	2015.26 (163.29)	0.359 (0.098)	686.34 (183.71)	0.736 (0.121)	393.83 (63.89)	4.308 (0.204)	2889.99 (486.85)	73.39 (5.44)
IN-F.GC2 - 4cm (a,b,c)	2144.43 (127.62)	0.485 (0.135)	1473.06 (161.79)	0.943 (0.165)	913.36 (75.85)	6.915 (1.476)	7399.15 (584.77)	60.75 (3.10)

3.3 Failure modes

The interface specimens were observed after pull-out tests to analyze the failure mode. Figures 4 a, b present the failure modes of pull-out test specimens. Depending on the type of carbon textile, the interface specimens give two failure modes, a failure mode with an abrupt way for IN-F.GC1 specimens (see Figure 4a), or progressive damage for IN-F.GC2 specimens (see Figure 4b). As results, it could be observed that IN-F.GC1 specimen has lost a part of its corps while there were clearly matrix valleys around the place of the warps of IN-F.GC2 specimens.



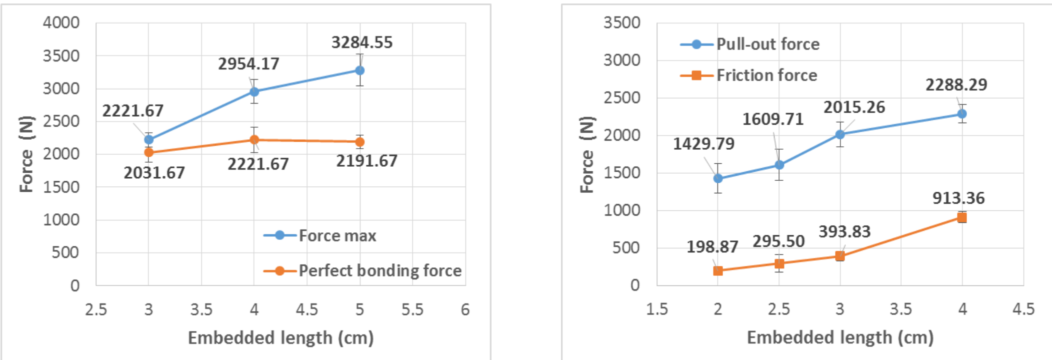
(a) (b)

Figure 4. Failure modes of pull-out test specimens; (a) for IN-F.GC1 and (b) for IN-F.GC2

4 DISCUSSION

4.1 Effect of embedded length on pull-out behavior

Regarding the effect of embedded length on the interface behaviour, it could be found that the maximum pull-out force increases gradually with the raise of this length. However, this tendency is not linear for all cases of different embedded lengths. When the embedded length was longer than a critical value (for example: 4 cm for IN-F.GC2), the textile/matrix interface would be damaged on each small part between two weft yarns. Therefore, the maximum pull-out force obtained wasn't limited value for the capacity of all interface lengths. On the other hand, IN-F.GC2 specimens with three other embedded lengths (2cm, 2.5cm and 3cm) gave an almost linear tendency of maximum pull-out force with the increase of embedded length. The same observation in maximum pull-out force could be found for the IN-F.GC1 specimens (see Figure 5a). The embedded length also influenced on the pure friction force of pull-out behaviour for the IN-F.GC2 specimens. In this case, an inverse effect was observed for IN-F.GC2 specimens with an embedded length of 4cm. After being damaged on a part, the interface length is enough long to maintain greater frictional force compared to that of other specimens with the smaller embedded length. Figure 5 shows the effect of embedded length on the pull-out force for IN-F.GC1 (a) and IN-F.GC2 specimens (b).



(a) (b)

Figure 5. Effect of embedded length on pull-out behavior; (a) for IN-F.GC1 specimens; (b) for IN-F.GC2 specimens

4.2 Effect of fibre treatment on pull-out behaviour

In comparison to the "force - slip" curves of pull-out behaviour between IN-F.GC1 and IN-F.GC2 specimens, it could be found the difference between the both: a softening behavior in the absence of the pure friction phase for IN-F.GC1 and another with a small phase of separation for IN-F.GC2 (see Figure 3). This difference can be explained by the reason from the textile treatment. With the epoxy resin treatment, the rigidity and strength of GC1 textile are very high. So, when the pull-out force transmits from the textile to the textile/matrix interface, this bond was broken almost at the same time along the embedded length. That's why there was a rupture with abrupt way after the debonding phase, and there wasn't the pure friction phase on the "force-slip" curves. Regarding the effect of amorphous silica treatment on pull-out behaviour of the IN-F.GC2 specimens, it gave good adhesion with the cementitious matrix. However, the rigidity and strength of this textile (GC2) are about 2 times lower than those of GC1. The shear force is therefore unevenly distributed on the embedded length of the interface. This cause conducted the progressive damage of each part of the embedded length. That's why the force had increased a few times after the first important drop of pull-out force.

5 CONCLUSION

As results obtained, some conclusions could be drawn for this work. The interface behavior of the carbon textile embedded in the cementitious matrix could be characterized by pull-out tests. The experimental results showed that the textile/matrix interface specimens gave a softening behavior with two or three phases. The embedded length affected to pull-out behavior, failure mode and total energy of the interface specimens. This is an increase in maximal pull-out force and pure friction force with the raising of embedded length. However, this tendency is not linear when the embedded length is longer than a critical value depending on the carbon textile. The effect of textile treatment on the pull-out response was also characterized. With an epoxy resin treatment, the IN-F.GC1 specimens gave a softening behavior with quick failure in the last phase. For IN-F.GC2 (GC2 treated by an amorphous silica product), it could be found progressive damage in the pure friction phase on the "force-slip" curves.

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