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Analysis of steel fibers pull-out. Experimental study

Facundo Isla *, Gonzalo Ruano, Bibiana Luccioni

CONICET, Argentina
Structures Institute, National University of Tucumán, Argentina

HIGHLIGHTS

- Pull-out tests of different steel fibers with different inclinations are presented.
- Fibers are pulled out from different types of mortar and concrete matrix.
- The effects of fibers geometry and inclination and matrix type are studied.
- Different types of fibers failure are analyzed.
- Matrix failure zone for the case of inclined fibers is measured.

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ABSTRACT

A series of experimental pull-out tests consisting of different types of steel fibers with different inclinations extracted from various types of matrix is presented. Based on experimental results, the complete pull-out process including fiber and matrix failure modes is analyzed to obtain conclusions that could serve as basis for the development of a numerical model for fiber reinforced concrete including pull-out mechanism. The anchorage effect of the hook, the effect of fibers geometry and slenderness, fibers inclination and matrix type and strength are studied. It is shown that fiber inclination affects fibers pull-out strength and can lead to fiber breakage. The differences in fibers pull out response from concrete and mortar are assessed and justified. It is recommended performing pull-out tests from concrete to calibrate numerical models for fiber reinforced concrete and to take into account fibers inclinations in these models.

1. Introduction

Due to the latest technological developments in structural concrete, high strength concretes can be obtained but, as a counterpart, the material becomes more brittle. The addition of fibers in this type of concrete improves material ductility. Fibers intercept the cracks delaying their propagation. If enough fibers are added to concrete and they are uniformly distributed, they prevent micro cracks coalescence improving the matrix apparent strength. Fibers presence favors the development of multiple smaller cracks. The most important difference in the mechanical behavior of fiber reinforced concrete (FRC) with respect to plain concrete is obtained in tension. The improvements are mainly related to the load transfer process from the matrix to the fibers through the cracks. Fibers pull-out is the main mechanism contributing to the FRC high toughness.

During the fibers pull-out, forces trying to prevent slippage are developed. In the case of straight smooth fibers, these forces are originated by adherence and friction in the fiber/matrix interface. If straight fibers are deformed or special processes are used to generate particular geometries like hooked fibers, with end buttons, with end paddles or twisted fibers, an additional mechanical component is obtained as a result of the anchorage effect provided by the fiber geometry. Depending on the fiber geometry, load can be transferred form the matrix to the fibers with or without sliding. However, fiber slippage is always desirable because it improves FRC ductility and toughness.

Steel fibers present elastoplastic hardening behavior up to a certain limit strain producing rupture. In most cases instead of failing, fibers are pulled out from the matrix after they have lost their adherence with the matrix. During the pull-out process a combination of debonding and sliding in the fiber/matrix interface takes place. Thus, the longer the fibers, the higher the pull-out strength.

* Corresponding author at: CONICET, Structures Institute, National University of Tucumán, Av. Independencia 1800, 4000 S.M. de Tucumán, Argentina.
E-mail address: fisla@herrera.unt.edu.ar (F. Isla).
URL: http://www.facet.unt.edu.ar/iest (F. Isla).

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As a result of increasing applications, many experimental studies have been carried out to investigate FRC properties and develop new design recommendations. Design is conditioned by many parameters like type, geometry and content of fibers, adherence strength, fibers and matrix strength, fibers distribution and orientation.

Fibers pull-out tests are used to study the anchorage mechanism of fibers in a cement matrix. The specimens used for these tests are usually characterized by a matrix body including a discontinuity that goes through the complete transverse section. The two parts of the specimen remain joint by one or more fibers. The test consists of fixing one end, applying load to the other end so as to separate both parts and recording the applied load and the separation produced. In some cases, only one-half of the specimen is used, leaving free one of the fiber ends and pulling from that end. The most frequently used specimens are dogbone, half dogbone, prismatic, cubic and cylindrical. Each type of specimens has a particular grip system. Dogbone specimens are fixed with rigid clamps designed with a special shape so that they can be coupled to the enlarged ends [1–3]. In the case of half bone specimens, one end is fixed with the same type of rigid clamp and on the other end the fiber is pressed with a plane clamp applying lateral pressure [4,5]. Prismatic specimens are held with parallel faces clamps [6]. Cubic and cylindrical specimens are held with rings [7–10]. Some researchers used adhesives to fix the specimen body to the load system [11,12]. This system has the advantage of avoiding lateral stresses that can distort pull-out response [7].

Fibers can be aligned or inclined respect to the longitudinal direction that is coincident with load direction. Pull-out tests are generally carried out with low loading rates.

There are many experimental results from pull-out tests [1–23]. Nevertheless, a great variability even for similar materials and tests is observed. There are few pull-out tests from concrete specimens and the dimensions of the matrix rupture zone caused by pull-out inclined fibers have not been measured.

A series of experimental pull-out tests of different types of steel fibers with different inclinations from various types of matrix are presented in this paper. Based on experimental results, the complete pull-out process including fiber and matrix failure modes is analyzed. The anchorage effect of the hook, the effect of fibers geometry and slenderness, fibers inclination and matrix type and strength are studied. Particularly, the combined action of these effects on final pull-out behavior is analyzed and practical design recommendations are presented.

2. Brief literature review

A brief description of the main results obtained in steel fibers pull-out tests by different authors is presented in this section.

2.1. Smooth, straight steel fibers

Pull-out tests of smooth straight steel fibers from different strength matrices were carried out by Naaman et al. [13]. They observed that smooth steel fibers with circular transverse section and straight axis, aligned with the pull-out direction, bear the pull-out action through adhesion and friction forces developed at the fiber/matrix interface [13]. In this way, the force applied to the fiber is transferred to the matrix. Two stages can be distinguished during the pull-out process, adhesion loss and slippage [13]. At the beginning of the first stage, the behavior of the fiber/matrix interface is elastic in its full length. Then, an elastoplastic behavior is developed in the more stressed zones, followed by the interface rupture in those zones generating a surface friction. Adherence takes place during elastic and plastic behavior. In a second stage, once the interface failed and a friction surface is generated in the full embedded length, the fiber begins to slide. Sliding also takes place during the first stage along the failed parts of the interface due to the fiber axial deformation but this slipping is negligible. During the second stage, load transfer from fiber to matrix is only due to friction forces. The peak load is attained for very low displacements at the first stage. Later, an abrupt drop of load is observed up to a certain load level called post peak load and this is the beginning of the second stage. As the fiber slides, interface length is progressively lost and thus, friction is reduced. Moreover, fiber slippage produces matrix wear and compaction around the fiber, reducing friction even more [13].

2.2. Hooked steel fibers

Adherence developed by smooth fibers is not enough for high performance cement composites and for this reason, irregular shape fibers that allow mechanical anchorage effect are most commonly used. This type of fibers requires large displacements to activate the effect of mechanical anchorage and so the hook becomes effective after matrix cracking. The mechanical anchorage effect is important to improve toughness, energy absorption capacity and the development of multiple cracks [14].

Like smooth straight fibers, hooked fibers also resist the pull-out action by adherence and friction but the hook provides a local effect at the fiber ends that increases the pull-out strength. This strength contribution is mainly due to the hook deformation [9]. The hook contribution depends on the fiber properties, the hook geometry (inclination angle, fiber diameter and hook length) [4,8,12,14–22].

2.3. Effect of fiber inclination

Fibers pull-out strength depends on fiber inclination so many authors have studied the effect of fiber inclination with respect to the crack plane (or to the load direction) [3,8,12,14,16,17].

Ductile fibers with low elasticity modulus can easily flex and work as dowels that can induce additional pull-out strength compensating the reduction provided by fiber inclination [14]. In the case of brittle fibers with high elasticity modulus, flexure can generate stresses that, added to the tension stresses, can produce premature fibers failures reducing the composite efficiency. The pull-out response also depends on the capacity of the matrix in the vicinity of the fibers to support local additional flexure without cracking.

Post peak load and the energy absorption capacity are functions of the fiber inclination.

Pull-out tests of fibers with an inclination of 30° showed an increase of strength with respect to aligned fibers but the pull-out strength decreases for greater inclinations [3,8]. Moreover, high strength matrixes can produce brittle fiber and matrix failure modes that lead to energy absorption capacity reduction during pull-out tests. These results show that the performance of fibers in FRC cannot be assessed from pull-out tests including only aligned fibers.

2.4. Fibers failure

Different authors [5,8,10,13,14,16] have observed that, under certain conditions, hooked fibers or, in general, deformed fibers can reach failure while being pulled out. Two different cases of fibers failure should be distinguished: total or partial failure. When failure takes place outside concrete or matrix it is called total failure because the pull-out force can not be longer transferred to the matrix. Alternatively, fiber failure can take place in the embedded part of the fiber. This case is called partial failure because part of the embedded length is lost but the remaining part continues transferring load to the matrix.

2.5. Matrix failure

Pull-out of fibers inclined with respect to the load direction generates matrix failure at the area where the fiber emerges from the matrix [8,16,17]. Consequently, the length of the fiber/matrix interface and thus, the pull-out strength, are reduced. There are no available experimental results in which the dimensions of the matrix rupture zone have been reported.

2.6. Influence of fibers and matrix strength

Bentur et al. [14] observed that while matrix strength has low influence on the pull-out strength of fibers with low carbon content, the increment of matrix strength generates increments in pull-out strength of high carbon content fibers.

Markovich et al. [7] concluded that the addition of short fibers to the matrix increases the pull-out strength but the increase of short fibers content did not generate significant increments in peak load.

Krishnadev et al. [23] concluded that pull-out strength is more sensitive to steel strength than to steel ductility. Nevertheless, the optimum steel properties also depend on the matrix strength.

3. Experimental program

Although there are many results from pull-out tests reported in the literature, a great variability of the results even for similar materials is observed. Moreover, data about the matrix rupture zone size for the case of inclined fibers were not found.

The main objective of the series of pull-out tests reported in this paper was to obtain a complete set of results in which the effect of fibers strength and shape (diameter, length, end shape), type of matrix and fiber inclinations can be analyzed for the materials locally available. A particular objective was the measurement of the matrix rupture zone dimensions. This information was used for the development of a numerical model for fiber reinforced concrete that includes fibers pull-out mechanism and will be presented in another paper.

The pull-out tests presented in this paper are part of a bigger experimental program including FRC characterization. Pull-out series consists of extraction of different types of steel fibers with different inclination from different types of matrix, two different strength mortars and concrete.

3.1. Steel fibers

The three different types of hooked end steel fibers (H1, H2, H3) used in the tests are described in Table 1 where f_y represents the yield stress, $\varnothing_f$ the fiber diameter and L the fiber length. To study the anchorage effect of the hook, straight fibers (S1, S2, S3) obtained from the same fibers (H1, H2, H3) cutting one of the hooks were also tested (see Fig. 1).

Table 1
Different types of steel fibers tested.

Fiber	f_y (MPa)		$\varnothing_f$ (mm)	L (mm)
	Provided by the manufacturer	Tests		
1	>800	860	1.00	50
2	>1100	1100	0.75	35
3	>2300	2470	0.71	60

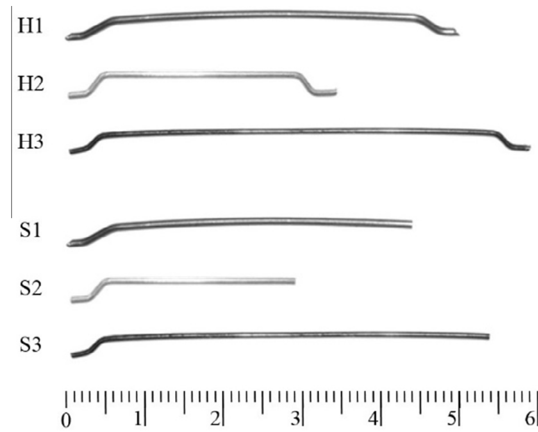

Fig. 1. Different types of steel fibers used in the tests.

In order to obtain their tension strength, tension tests were carried out for the fibers H1, H2 and H3. The tension tests were performed with a servo-controlled press of 500 kN capacity using displacement control with a rate of 2 μm/s.

The values of the tension yield stress provided by the manufacturer and the average yield stress obtained in tension tests are presented in Table 1. Measured yield stress was always equal or greater than that provided by the manufacturer. The experimental results for tension yield stress evidence three different steel qualities. The stress–strain curves obtained for the fibers tension tests are shown in Fig. 2. In all cases the fibers behavior was almost elastic perfectly plastic.

3.2. Matrix

Three different types of matrix were used, two different types of mortar M30 and M80 and a concrete C80. Both mortars were obtained from the corresponding concrete running them through a sieve to remove the coarse aggregate. Self consolidating concrete was used in order to achieve a good compaction during pouring in small molds. The concrete corresponding dosages are presented in Table 2. Portland cement CPF40 was used for C30 and M30 while CPN50 was used for C80 and M80. The maximum size of coarse aggregate was 9.5 mm and the sand fineness modulus was 3.

Complementary tests were performed on concrete specimens to evaluate elasticity modulus, compression strength and flexure strength. The average compression strength measured at 28 days were 37.3 MPa and 89.7 MPa, the measured elasticity modulus were 28.9 GPa and 40.5 GPa for C30 and C80, respectively.

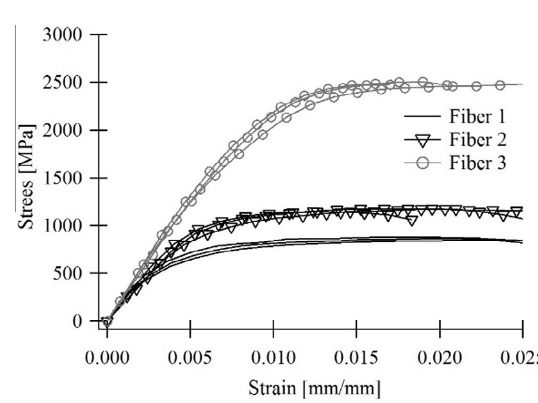

Fig. 2. Stress–strain curves from fibers tension tests.

Table 2
Concrete and mortar dosages.

Material	C30 (kg/m^3)	C80 (kg/m^3)
Cement	(CPF40) 470	(CPN50) 567
Water	179	170
Sand	934	868
Binder	787	820
Additive	3.29	3.97

3.3. Pull-out specimens

Cylindrical specimens were used for pull-out tests (see Fig. 3). The dimensions of the specimens were defined taking into account the maximum size of coarse aggregate. Half the fiber length was embedded as indicated in Fig. 3 where the case of a fiber with inclination φ is sketched. The inclinations tested were $\varphi = 0°$, $\varphi = 30°$ and $\varphi = 60°$ that discreetly span the range $0° \leqslant \varphi < 90°$ and are the same values used in other pull-out studies [3,8,12,14,16,17].

Specimens are identified with three codes separated by scripts. The first code indicates the fiber type (Fig. 1), the second code identifies the matrix (Table 2) and the third code represents the fiber inclination, φ(°). As an example, H1-C80-30 identifies the pull-out test of hooked fiber 1, from concrete C80 with an inclination of 30°.

3.4. Test setup

The hydraulic servo controlled press with 500 kN capacity shown in Fig. 4 was used for the tests. For operational reasons, the specimens were tested upside down. The free end of the fiber was clamped with the bottom hydraulic grip (see Fig. 4c) while a specially designed grip was used at the other end to pull upwards from the specimen body (see Fig. 4b).

Load was recorded with a load cell composed of two dynamometric rings with a linear variable differential transformer (LVDT) (see Fig. 4b). In this way, a sensibility of 2 N was achieved in load measurements.

Two LVDT with 50 mm range and 5 μm sensibility, located at both sides of the specimens were used to record the displacements. Displacement was obtained as the mean of the displacements measured by the two LVDT. Additionally, two LVDT with 5 mm range and 0.5 μm sensibility were placed, one on each side of the specimen and the measurements were averaged. While the 50 mm range LVDT were used to record displacements, the 5 mm range LVDT were located to record the slipping beginning with better precision and were maintained during the whole test to check the other LVDT measurements. They were also used to position the mobile head during the test montage, keeping a separation of 1 mm between the border of the grip used to clamp the fibers and the specimen face. An external data acquisition system composed of data boards USB-1616FS, a notebook and acquisition and monitoring software, were used.

The tests were performed with displacement control. First, a rate of 5 μm/min was applied up to a displacement of 50 μm. Then, the velocity of the test was increased to 100 μm/min up to a displacement of 1000 μm and finally, the velocity was increased to 500 μm/min until a total displacement of 25,000 μm was achieved.

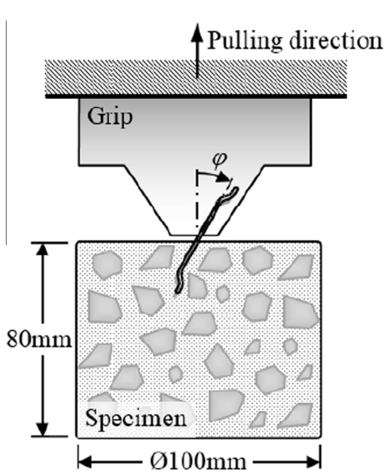

Fig. 3. Pull-out specimens.

4. Test results

The load–displacement of the end of the fiber curves recorded in the different tests are presented in this section. The results are grouped taking into account the different variables defining the specimens. For each type of specimen (fiber–matrix–fiber inclination), five tests were performed to have representative results. Some of the results were discarded because they were atypical.

4.1. Mortar specimens

The load–displacements curves obtained for pull-out tests of fibers S1 (straight) and H1 (hooked) from mortar M30 matrix are presented in Fig. 5a and b, respectively. The comparison of both figures clearly evidences the anchorage effect provided by the fiber hook that increases pull-out strength and almost duplicates residual pull-out strength. The variability of the results is greater for the case of hooked end fibers. For these fibers, the pull-out response is mostly dependent on the hook geometry and thus the variability of the results observed in Fig. 5b can be partly attributed to variations in hook geometry.

Load–displacement curves obtained from pull-out test of fiber H1 from mortar M80 are presented in Fig. 6. The comparison of Fig. 6 with Fig. 5b shows the effect of increasing mortar strength on fibers pull-out strength. Some of the curves indicated with crossings on Fig. 6 show an abrupt load drop that corresponds to partial fiber failure. Due to the high strength of the mortar, matrix channel preserved its integrity and the fibers might be severely strained to follow the channel during slipping. Some of them could not resist this deformation and failed before being completely extracted from matrix. Comparing Figs. 5b and 6 it can be noted that the residual response is smoother in the case of more resistant matrix that enforces the fiber to straighten more to slide and in this way, the friction due to the residual deformation of the fiber end is reduced.

4.2. Concrete specimens

The results obtained for pull-out tests of steel fibers from concrete matrix are presented in this section. First, the results obtained for different types of fibers with and without hook are presented and then, the curves obtained for one of the fibers pulled-out with different inclinations are shown.

Test results for pull-out tests of fiber 1 without and with hook form concrete C80 at an inclination $\varphi = 0°$ are presented in Fig. 7a and b, respectively. The pull-out curves in Fig. 7a corresponding to straight fibers are characterized by a peak load followed by an abrupt drop. For displacements greater than 10 mm, the load is maintained. This residual load can be attributed to the existence of imperfections in fibers geometry and coarse aggregates in the matrix that increase final friction. Fig. 7b corresponding to hooked fibers H1 shows that pull-out strength is higher than

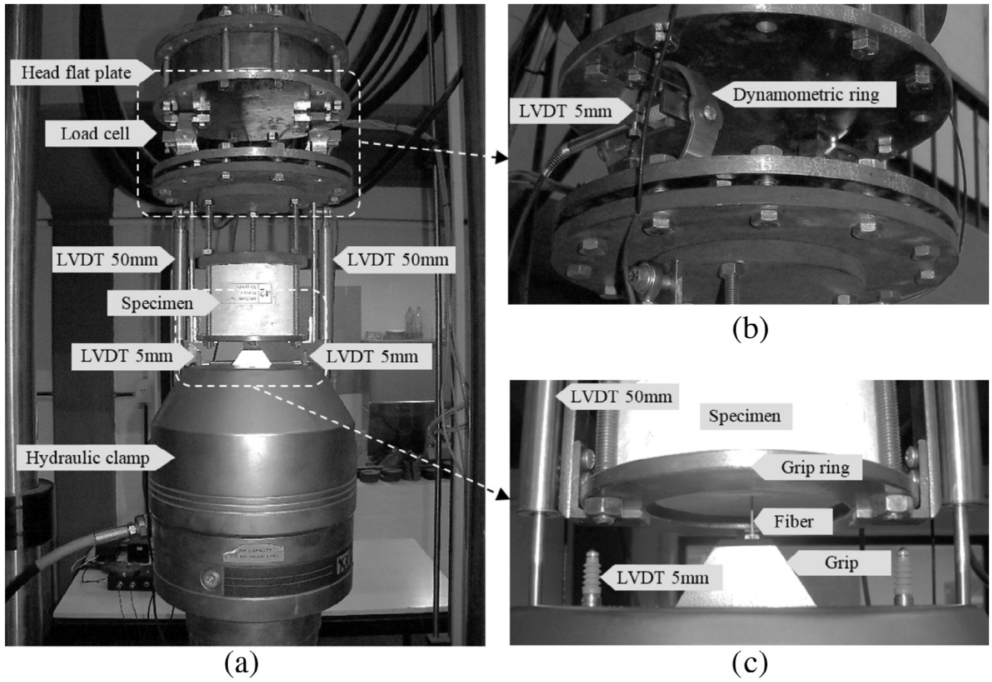

Fig. 4. Test setup. Measurement devices.

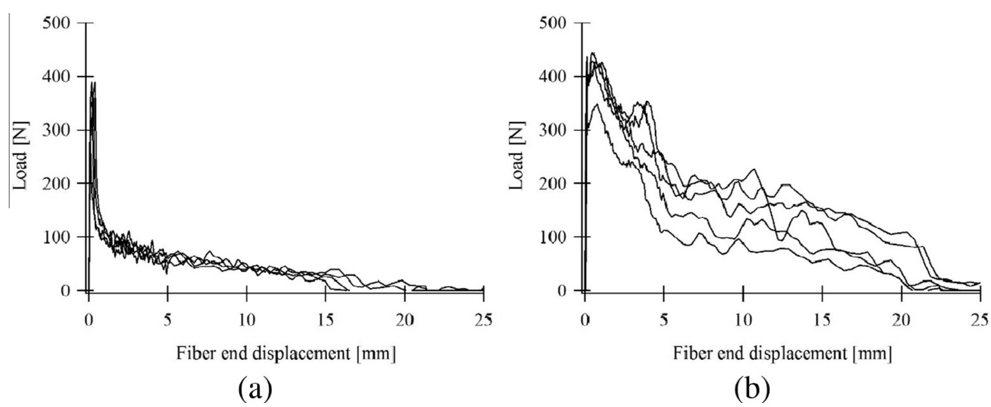

Fig. 5. Load–displacement curves obtained from pull-out tests of fiber 1 without and with hook from mortar M30. (a) S1-M30-0, (b) H1-M30-0.

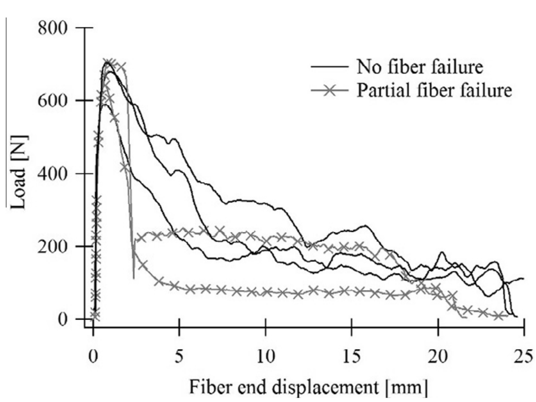

Fig. 6. Load–displacement curves obtained from pull-out test H1-M80-0.

that obtained for the same fibers without hook but most of the fibers partially failed. It can also be observed that the shape of the curves in the region between 6 and 25 mm displacements is different from the shape of the curve obtained for the same fibers but extracted from mortar matrix (Fig. 6). Residual pull-out response presents fluctuations and more variability for the case of concrete matrix. Both effects can be attributed to coarse aggregates in concrete matrix.

Test results for pull-out tests of fiber 2 without and with hook from concrete C80 at an inclination $\varphi = 0°$ are presented in Fig. 8a and b, respectively. The shapes of the pull-out curves are similar to those obtained for fiber 1. Two of the hooked ended fibers H2 presented total failure during the pull-out (line with circles and line with triangle) while one of them presented partial failure (lines with crossings). For this case, the fibers are working near their limit strength, so slight variations of the matrix strength or the fibers geometry can lead some of them to fail while some of them preserve their integrity.

Test results for pull-out tests of fiber 3 without and with hook form concrete C80 at an inclination $\varphi = 0°$ are presented in Fig. 9a and b, respectively. The shape of the pull-out curves obtained for straight fibers S3 (Fig. 9a) is similar to that obtained for straight fiber S1 (Fig. 7a). For displacements greater than 10 mm, the load is maintained but experimental results show great

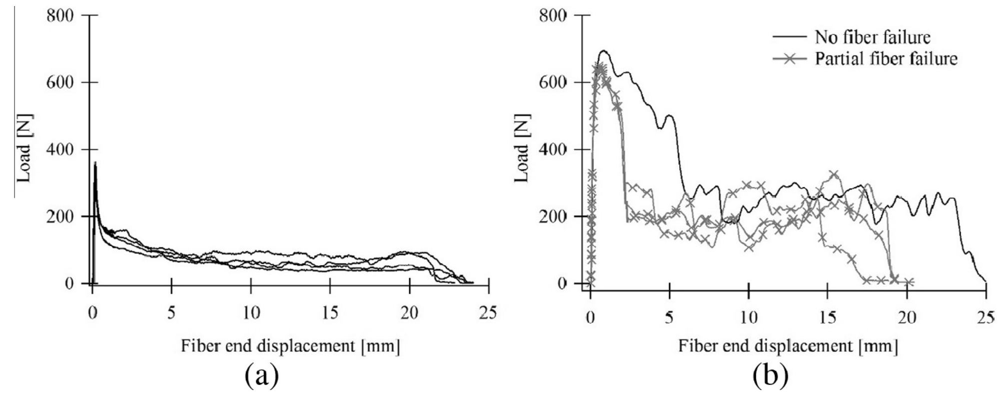

Fig. 7. Load–displacement curves obtained from pull-out tests of fiber 1 without and with hook from concrete C80. (a) S1-C80-0, (b) H1-C80-0.

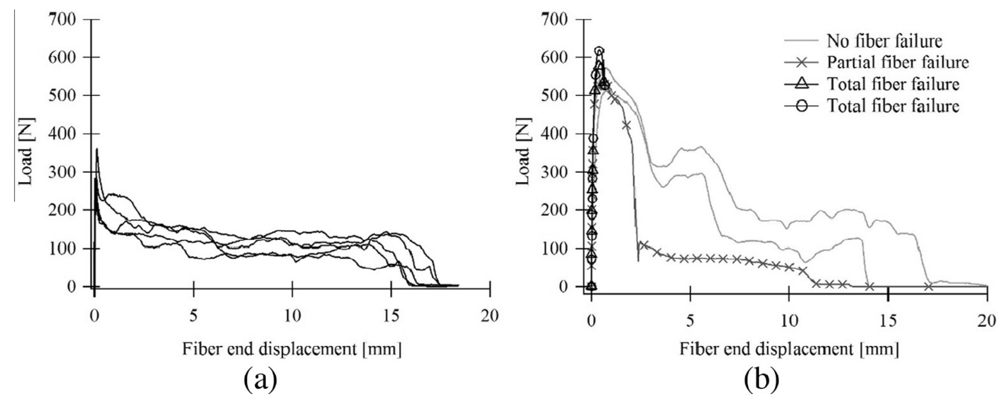

Fig. 8. Load–displacement curves obtained from pull-out tests of fiber 2 without and with hook from concrete C80. (a) S2-C80-0, (b) H2-C80-0.

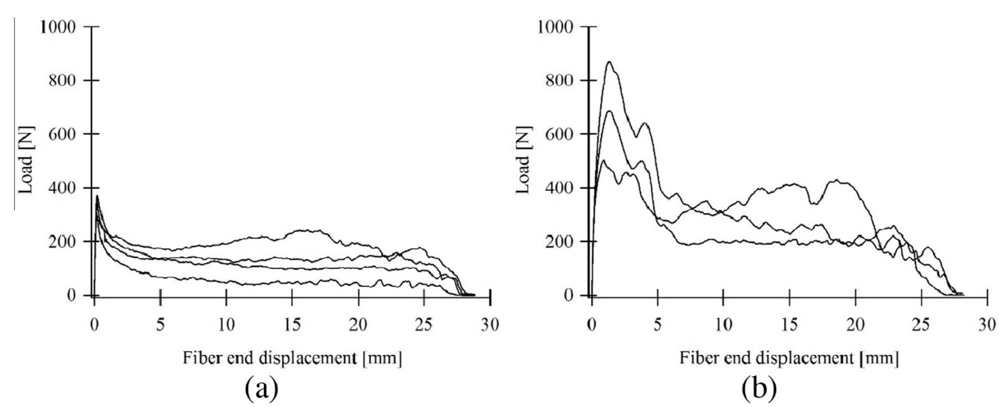

Fig. 9. Load–displacement curves obtained from pull-out tests of fiber 3 without and with hook from concrete C80. (a) S3-C80-0, (b) H3-C80-0.

variability and greater residual load than for fibers S1. The differences can be attributed to the imperfections in fibers geometry that were not perfectly straight together with the greater fiber strength. The pull-out curves obtained for fibers H3 (Fig. 9b) are smooth and do not show drops because the fibers are more resistant and did not fail during the extraction tests. The variation in maximum peak load is greater than for the case of weaker fibers. In the case of more resistant fibers, the load required to deform the hook is greater and pull-out load is more sensible to the matrix imperfections and hardness variations. The variability of the matrix hardness is more important in the case of concrete than in the case of mortar. These two facts can be responsible for the differences in maximum pull-out load obtained for fibers H2 when being extracted from a concrete matrix.

Test results for pull-out tests of hooked fiber H1 form concrete C80 at different inclinations, $\varphi = 30^\circ$ and $\varphi = 60^\circ$ are presented in Fig. 10a and b, respectively. The curves obtained are very different from those obtained for the same fibers and matrix with $\varphi = 0^\circ$. Pull-out strength slightly increases for $\varphi = 30^\circ$ and then decreases for $\varphi = 60^\circ$. Most of the hooked fibers presented total failure when tested with an inclination of $\varphi = 30^\circ$ and some of them fail when the inclination is increased to 60°.

5. Results analysis

The results obtained for the different tests performed are analyzed and compared in this section. In coincidence with the results

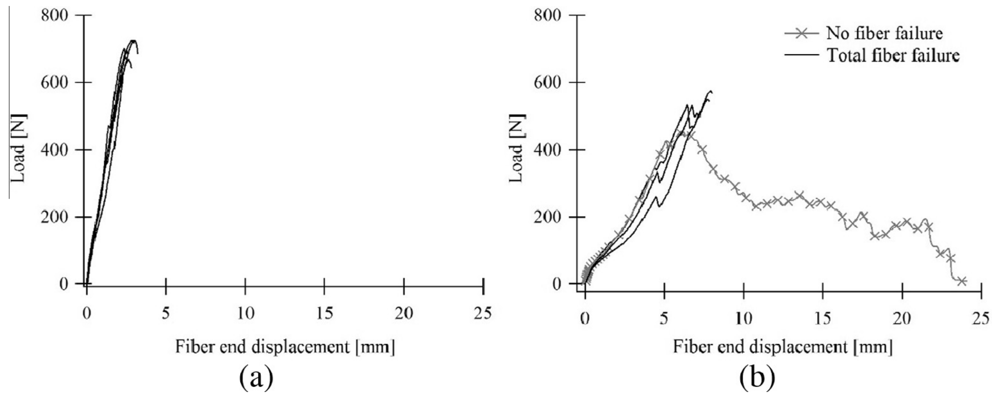

Fig. 10. Load–displacement curves obtained from pull-out tests of hooked fiber 1 from concrete C80 with different inclinations. (a) H1-C80-30, (b) H1-C80-60.

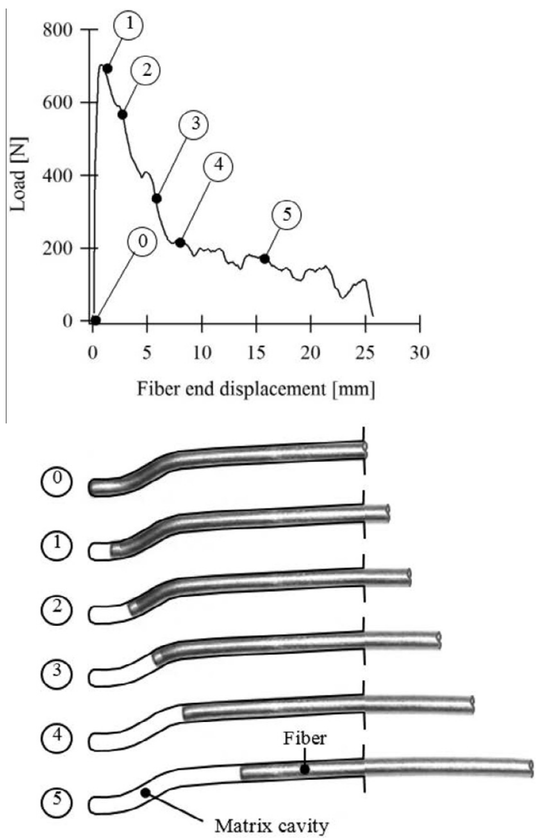

Fig. 11. Relation between pull-out curve shape and fiber sliding process. H1-C80-0.

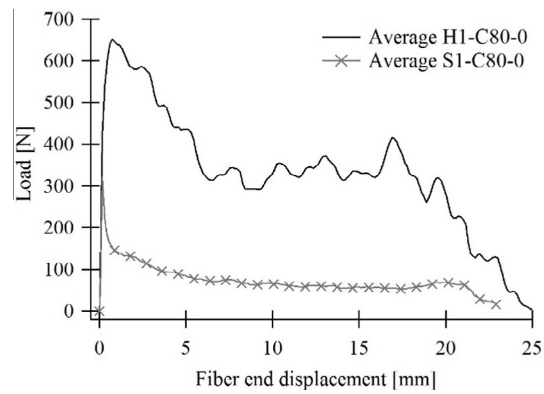

Fig. 12. Average pull-out curves. Hook effect in fibers 1.

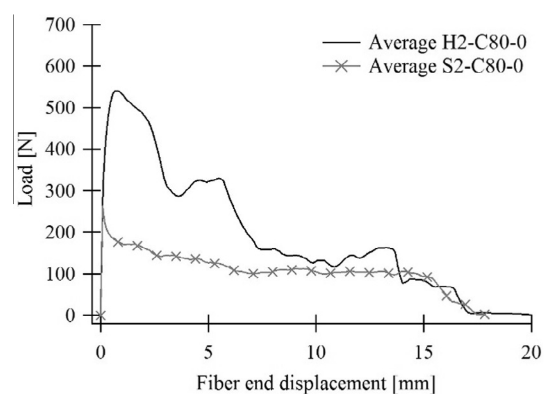

Fig. 13. Average pull-out curves. Hook effect in fibers 2.

obtained by other researchers [1–23], high variability of experimental results obtained for similar specimens is observed. This dispersion in experimental results can be attributed to the variability of matrix properties and to the variability observed in hook geometry for the same type of fibers. The last statement is supported by the fact that in the case of mortar matrix, the variability observed for straight fibers is lower than that observed for hooked fibers, see for example Fig. 5. The variability of the maximum pull-out load also increases with the fiber strength.

From experimental results it is observed that pull-out load–displacement curves present characteristic shapes mainly depending on their axis geometry: the number of curve parts, the length of those curve parts and their curvature ratio. The shape of the pull-out curve and the pull-out strength also depend on the fiber diameter and its surface texture and on the matrix strength. Depending on the fiber strength, they can fail while they are sliding, producing abrupt load drops in load–displacement pull-out curves.

A typical load–displacement curve obtained from pull-out test of hooked fiber H1 from mortar M80 is shown in Fig. 11. The relation of the different parts of the curve with the fiber sliding process is indicated in Fig. 11. The characteristic zones of the curve are indicated with consecutive numbers and corresponding positions of the fiber are indicated below. As the fiber goes out of the matrix cavity, the contribution of curve parts is lost and pull-out strength decreases.

5.1. Hook effect

The average pull-out curves corresponding to hooked fibers and straight fibers (the same fibers without hook) are presented in

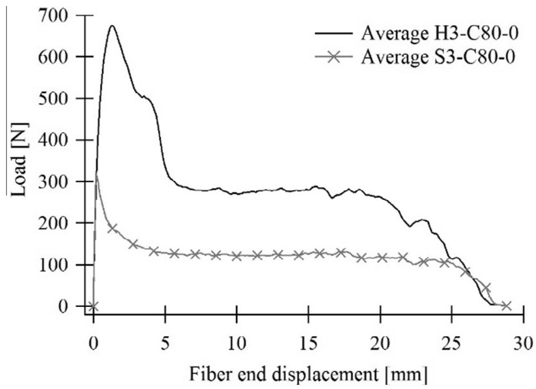

Fig. 14. Average pull-out curves. Hook effect in fibers 3.

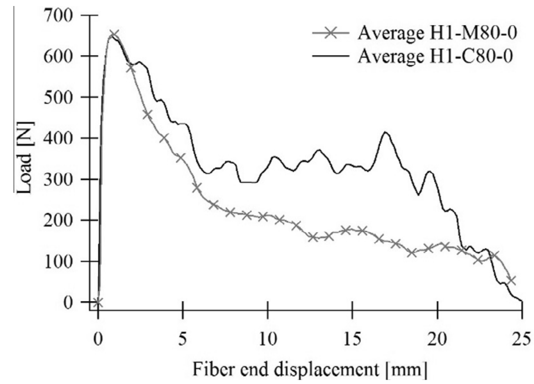

Fig. 16. Average pull-out curves for different matrix types. H1-M80-0 and H1-C80-0.

Fig. 12–14. All the curves correspond to fibers pulled-out from concrete with an inclination $\varphi = 0°$. Curves corresponding to fibers that failed during the pull-out process were not considered to obtain the average curve. The anchorage effect provided by the hook is evident in all cases.

It can be observed in Fig. 12 corresponding to fibers H1 and S1 that even for displacements greater than 6 mm, when the hooked fiber has theoretically been straightened by the slipping process, the pull-out strength is still greater than that corresponding to the originally straight fiber. This result can be attributed to the remaining irregularities at the fibers ends once the hook has been straightened. Fig. 15a shows the initial geometry of the hooked end and the remaining irregularities are presented in Fig. 15b. These irregularities contribute to the friction with the matrix channel and thus, increase the friction load [10,21]. The friction mechanism is schematized in Fig. 15b. Two photographs showing the initial geometry and the irregularities in the fiber end when it has been completely pulled-out are presented in Fig. 15c. The same friction effect can be observed in Fig. 13 and Fig. 14 corresponding to fibers H2, S2 and H3, S3, respectively. Nevertheless, this friction effect is less than that observed for fiber 1 because fiber 2 and fiber 3 have smaller diameters and so the irregularities remaining once the hook has been straightened are also smaller. Comparing Figs. 13 and 14, corresponding to fibers H2 and H3 that have slightly different diameters, it can be observed that the hook effect is greater in fiber 3 than in fiber 2, particularly in the residual pull-out strength. This difference can be attributed to the greater strength of fiber 3 that makes it more difficult to straighten it.

5.2. Effect of matrix type and strength

The average pull-out curves corresponding to fiber H1 extracted from a mortar M80 and concrete C80 are presented in Fig. 16 for comparison. The initial response, up to 5 mm displacement, is similar for both matrix types but for greater displacements, the curve corresponding to mortar matrix is smoother and exhibits lower residual strength than that corresponding to concrete matrix. The observed difference can be attributed to the presence of coarse aggregate in concrete that, together with the remaining irregularities at the fiber end, increase the residual pull-out strength.

The average pull-out curves obtained for fiber H1 extracted from two different strength mortar matrix, M30 and M80 are presented in Fig. 17 for comparison. It can be observed that fibers extracted from greater strength mortar present greater pull-out strength. It should be noted that for the case of matrix M30 (lower mortar strength) no fiber failed while for the case of mortar M80 (greater strength) some of the specimens presented partial failure. Accordingly, two average curves are included in Fig. 17 for the case of matrix C80, one corresponding to fibers that did not fail and one corresponding to fibers that failed while being pulled-out. When the matrix strength increases, pull-out strength also increases and can reach fiber strength producing fiber failure. Moreover, when matrix strength increases, matrix stiffness also increases forcing the fibers to deform more in order to slide.

5.3. Effect of fibers inclination

The pull out of inclined fibers is sketched in Fig. 18 that includes a detail of the zone where the fiber emerges from the matrix. The average pull-out curves for different fibers inclinations φ are presented in Fig. 19 for comparison. These curves are similar to those obtained by other authors [8,12,14,22].

It can be observed that for a given load level, the corresponding displacements increase with the increase of fiber inclination angle φ. This effect can be attributed to the matrix failure in the surrounding area from where the fiber emerges (Fig. 18b). This

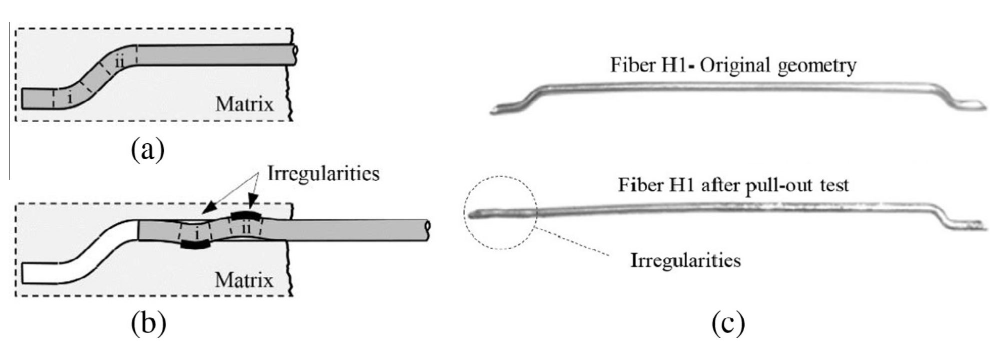

Fig. 15. Friction due to remaining irregularities once the hook has been straightened. (a) Initial position, (b) position after 6 mm sliding and (c) fiber end after pull-out.

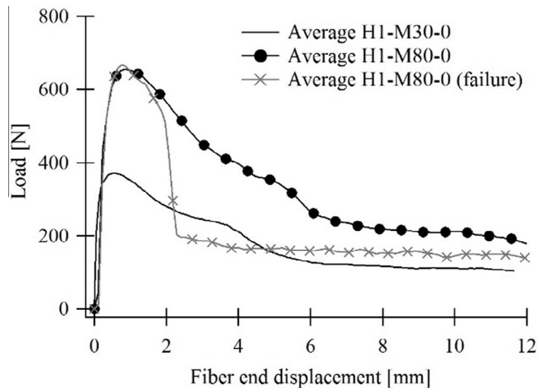

Fig. 17. Average pull-out curves for different strength mortar matrix. H1-M30-0 and H1-M80-0.

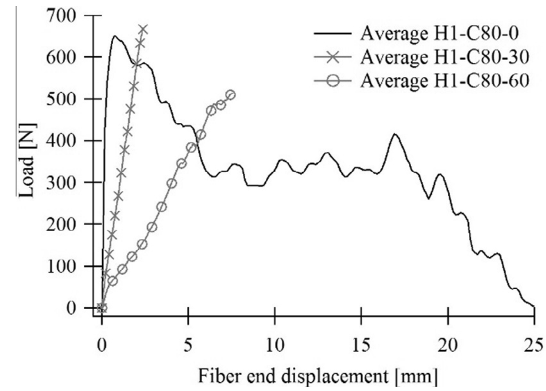

Fig. 19. Average pull-out curves for different fibers inclinations. H1-C80-0, H1-C80-30 and H1-C80-60.

matrix failure allows the fiber axis changing its initial geometry. The fiber rotates and generates displacement of the fiber free end without slipping of the embedded part of the fiber.

In the point where the inclined fiber emerges from the matrix, it is subjected to combined tension and bending but tension is dominant. The fiber fails when axial strain exceeds some limit value. The maximum pull-out load for fibers inclined 30° is close to the fiber uniaxial tension strength. Some fibers inclined 60° fail and some of them do not fail. In this case, the increase of the grip clamping force required to prevent rotation of the gripped end can lead to fiber failure for lower loads than for the case of less inclined fibers.

5.4. Fibers failure

Fig. 11 corresponds to a fiber that does not fail during pull-out. Fiber failure was observed in some of the tests (see Figs. 6, 7b, 8b and 10). When fiber failure takes place inside the matrix, part of the fiber can go on transmitting the pull-out load. In contrast, when fibers fail outside the matrix, load transferring capacity is abruptly lost. This last type of failure is typical of inclined fibers pull-out tests.

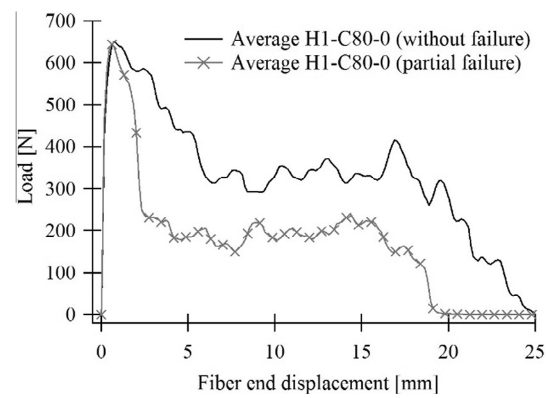

Fig. 20. Average pull-out curves (H1-C80-0). Comparison of fibers exhibiting failure with fibers that do not fail.

In both cases, fiber failure can be detected from pull-out curves shape. As illustration, average pull-out curves obtained for pull-out tests of hooked fibers from concrete matrix are presented in Fig. 20 where the curves corresponding to a fiber that did not exhibit

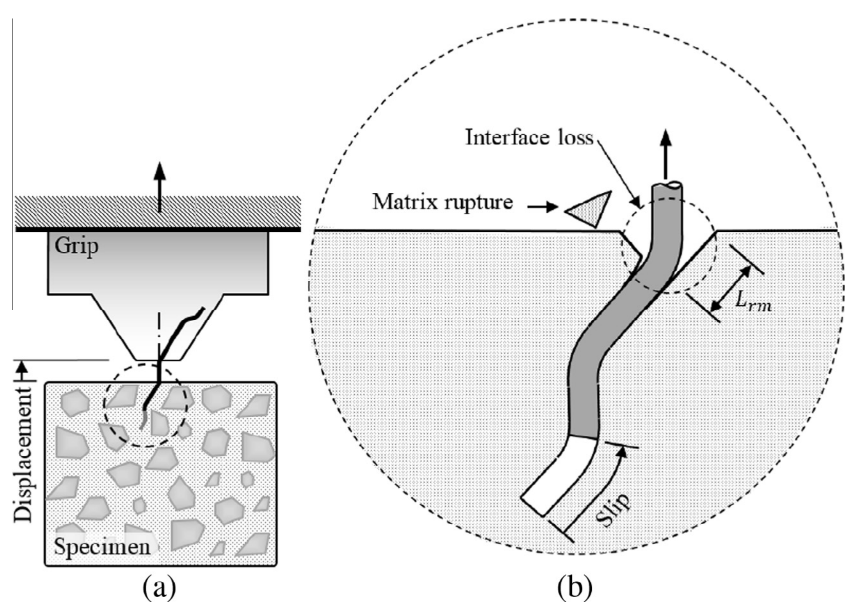

Fig. 18. Pull-out test of an inclined fiber. (a) Fiber inclination during the test; (b) detail of the zone where the fiber emerges from the matrix.

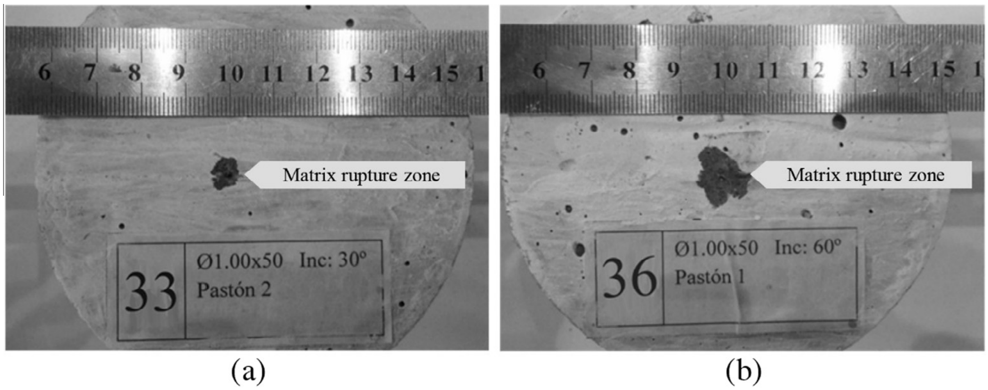

Fig. 21. Matrix rupture for different fiber inclinations. (a) $\varphi = 30°$; (b) $\varphi = 60°$.

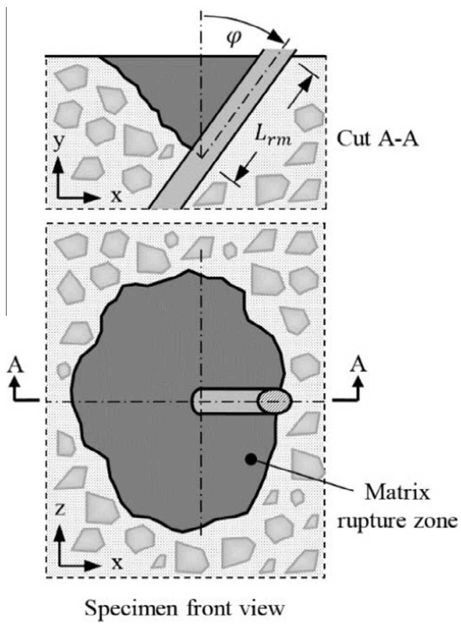

Fig. 22. Matrix rupture zone dimensions.

Table 3
Matrix rupture length L_{rm}.

H1-C80-30°		H1-C80-60°	
Test	L_{rm} (mm)	Test	L_{rm} (mm)
1	3.1	1	6.9
2	2.9	2	7.4
3	3.0	3	7.0
4	3.2	4	7.8
5	3.5	5	7.1
$\bar{L}_{rm}$	3.14	$\bar{L}_{rm}$	7.24
s_{rm}	0.23	s_{rm}	0.37

failure and to a fiber that exhibited partial failure are compared. In most of the experimental results presented, it can be observed that fibers failure takes place for a displacement of approximately 2 mm. This result can be explained observing fibers hook geometry that present two curve parts with opposite curvatures separated approximately 2 mm. When the curve part closer to the fiber end passes by the zone where the other curve part was initially located, it must suffer a great deformation in opposite direction that, together with an axial load close to uniaxial tension strength, can produce fiber failure.

5.5. Matrix failure in inclined fibers pull-out

The specimens with inclined fibers presented matrix rupture. Photographs of specimens with fibers inclinations $\varphi = 30°$ and $\varphi = 60°$ are shown in Fig. 21 where the matrix rupture zone can be identified. The surface of the failure zone is, in general, very irregular, but could be approximately described by a conical surface. The dimensions of the rupture zone depend on the fiber inclination angle φ.

Once the specimens with inclined fibers have been tested, the length of the matrix rupture zone L_{rm} was measured with a gauge, see Fig. 21a, b and Fig. 22 where the failure zone is sketched. The results are presented in Table 3, together with the average value $\bar{L}_{rm}$ and the standard deviation S_{rm}. From Fig. 21 and Table 3 it is clear that the dimensions of the matrix rupture zone increase with the fiber inclination angle φ.

6. Conclusions

The following conclusions can be stated from the pull-out tests presented and the corresponding experimental results.

Very high variability of pull-out force for the same type of fiber and matrix is obtained. Higher variability is found for concrete matrix due to the typical variability of coarse aggregate. Due to the variability of hook geometry, dispersion is higher for hooked fibers than for straight fibers and it also increases with the fibers strength.

Due to the mechanical anchorage effect provided by the hook that increases pull-out strength, there is a great difference between the pull-out response of straight fibers and that of hooked fibers. In straight fibers, the increase of embedded length produces an increase of pull-out strength. In contrast, for hooked fibers, pull-out strength strongly depends on the hook shape and embedded length plays a secondary role in pull-out strength. Even when the hook has apparently been straightened, there are still some remaining irregularities that lead to greater residual pull-out strength than for the case of straight fibers.

Pull out strength increases with matrix strength. The presence of coarse aggregate in concrete matrix affects pull-out strength. On one side, it reduces the fiber/matrix interface strength since it reduces the cement paste retraction around the fiber, reducing the misfit effect [24]. On the other side, the presence of coarse aggregate increases the mechanical anchorage effect of hooked fibers with respect to mortar matrix. This effect is higher for the case of low strength concrete for which the difference between the mortar strength and strength of the coarse aggregate is higher. The pull-out strength from a concrete matrix is always greater than that from a mortar matrix. The difference in peak load is not very important but the residual strength presents important variations according to the matrix type. For this reason, it is better to use concrete specimens to obtain the pull-out response as they better represent the behavior of fibers in FRC.

The pull-out behavior of inclined fibers present some differences with respect to the case of aligned fibers. The displacement corresponding to a certain pull-out force is always greater for inclined fibers than for aligned fibers. The difference is due to the matrix failure that reduces the embedded length and allows fiber rotation producing additional displacement without fiber slipping. This effect should be taken into account when modeling pull-out response of fibers.

Both for the case of straight fibers and hooked fibers, it is desirable that fibers slip before failing during the pull-out process. Under certain conditions, fibers can exhibit partial or total failure. Total failure is characterized by fiber failure outside the matrix or near the beginning of the embedded part of the fiber and causes the total loss of load transmitting capacity. For the case of hooked fibers, partial fiber failure can take place due to the excessive fiber deformation during the pull-out process. This type of fiber failure produces a drop in load transfer capacity but the intact part of the fiber continues transmitting loads. Experimental results show that fibers failure is strongly dependent on the relation between matrix and fibers strength. This relation should be carefully analyzed when designing FRC in order to prevent fibers failure.

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