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Analysis of steel fibers pull-out. Experimental study

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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.

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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