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Effect of loading rates on pullout behavior of high strength steel fibers embedded in ultra-high performance concrete

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ABSTRACT

In this paper single fiber pull-out performance of high strength steel fibers embedded in ultra-high performance concrete (UHPC) is investigated. The research emphasis is placed on the experimental performance at various pullout rates to better understand the dynamic tensile behavior of ultra-high performance fiber reinforced concrete (UHP-FRC). Based on the knowledge that crack formation is strain rate sensitive, it is hypothesized that the formation of micro-splitting cracks and the damage of cement-based matrix in the fiber tunnel are mainly attributing to the rate sensitivity. Hereby, different pull-out mechanisms of straight and mechanically bonded fibers will be examined more closely. The experimental investigation considers four types of high strength steel fibers as follows: straight smooth brass-coated with a diameter of 0.2 mm and 0.38 mm, half end hooked with a diameter of 0.38 mm and twisted fibers with an equivalent diameter of 0.3 mm. Four different pull out loading rates were applied ranging from 0.025 mm/s to 25 mm/s. The loading rate effects on maximum fiber tensile stress, use of material, pullout energy, equivalent bond strength, and average bond strength are characterized and analyzed. The test results indicate that half-hooked fibers exhibit highest loading rate sensitivity of all fibers used in this research, which might be attributed to potential matrix split cracking. Furthermore, the effect of fiber embedment angles on the loading rate sensitivity of fiber pullout behavior is investigated. Three fiber embedment angles, 0°, 20°, and 45°, are considered. The results reveal that there is a correlation between fiber embedment angle and loading rate sensitivity of fiber pullout behavior.

1. Introduction

The bond behavior between fiber and cementitious matrix is a key property for the material performance of fiber reinforced concrete. Numerous studies have been carried out to investigate the interfacial bond property by single fiber pullout tests. Naaman and Najm [1], Banthia [2], Sujiravorakul [3], Robins et al. [4], Kim et al. [5], Cunha et al. [6] and Wille et al. [7] explored the different pullout mechanisms of straight, end-hooked, and twisted fibers embedded in high strength or ultra-high strength cementitious matrices.

Although studies on single fiber pullout behavior under quasi-static condition are comprehensive, only a few researches have been conducted tests under dynamic conditions. Gokoz and Naaman [8] investigated the effect of loading rate on the pullout behavior of three types of fibers, smooth steel, glass and polypropylene, in mortar at loading velocities varying from 0.042 mm/s to 3000 mm/s. They revealed that polypropylene fibers showed strong dependence on loading velocity whereas smooth steel fibers exhibited no obvious loading rate sensitivity, and concluded that the friction effect was insensitive to loading velocity. Bindiganavile and Banthia [9] investigated the pull out response of three types of polymeric fibers and one type of flat end steel fiber under impact loading. They concluded that bond strength of all fiber types is sensitive to loading rates. Banthia and Trottier [10] performed pullout tests on deformed steel fibers under static & dynamic conditions and concluded that deformed steel fibers exhibit higher pullout resistance under dynamic conditions. Kim et al. [5] investigated the loading rate effect on the pullout behavior of deformed steel fibers and concluded that twisted fiber shows more rate sensitivity than end-hooked fiber for matrix strength ranging from 28 MPa to 83 MPa. Their results show that the rate sensitive behavior of twisted fibers is dependent on matrix strength. Abu-Lebdeh et al. [11] investigated the rate dependency of deformed and smooth steel fibers embedded in matrices of

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strength ranging from 43 MPa to 196 MPa. While their results show that smooth fibers are rate independent, the rate dependent pull out response of deformed fibers is influenced by the embedment length and the matrix strength.

To the best of the author's knowledge to date, there is no other comprehensive research published on single fiber pullout embedded in ultra-high performance matrix at various loading rates. Exploring the pullout performance of high strength steel fibers at various loading rates will help to better understand the dynamic tensile behavior of ultra-high performance fiber reinforced concrete (UHP-FRC).

2. Objectives

The objectives of this research are: 1) to evaluate and compare the effect of loading rates on the bond properties of brass-coated straight steel fibers and deformed steel fibers embedded in UHPC, 2) to investigate the effect of embedment angle on bond properties under different loading rates. Based on these objectives, fiber type, fiber embedment angle, and loading rate have been selected as variables in this research.

3. Background information and hypothesis

Fig. 1 illustrates the shape of different types of fibers and their bond mechanism during fiber pullout. While straight smooth fibers (S-fiber) develop their bond strength mainly due to adhesion and friction along the fiber surface, end-hooked fibers (H-fibers) and twisted fibers (T-fibers) develop their bond strength mainly due to mechanical bond at the fiber end and along the entire fiber length, respectively. Both mechanisms require plastic deformation to straighten the fiber. The increase in pull-out resistance of deformed H- or T-fibers in comparison to S-fibers is limited by the bending resistance of the end hook (pulley approach [12]) and by the torque resistance [3], respectively, assuming no fiber rupture or matrix damage.

The relationship between induced fiber tensile stress and pull out slip is summarized in Fig. 2. Based on the results in Refs. [1,3–6], Fig. 2a shows the typical stress-slip curve of high strength steel fibers (tensile strength of approximately 3000 MPa, 435 ksi) embedded in high strength matrix (strength of 55–60 MPa, 8–8.7 ksi). Comparable fibers embedded in ultra-high strength matrix (strength of 194 MPa, 28.1 ksi) show a significant higher induced fiber tensile stress during pull out and thus increased material utilization. This leads to the conclusion that the mechanical bond capacity of the H- and T-fiber through fiber straightening could not be fully utilized in the lower strength matrix. Local matrix failure, such as crushing and micro split cracking, might be the reason for the limitation of pullout capacity.

Based on the mechanical equations for H-fibers provided by Alwan et al. [12] and for T-fibers provided by Sujiravorakul [3], Wille [13] calculated the theoretical contribution due to friction and mechanical bond and concluded that the pullout capacity had been limited by matrix failure (see Fig. 3).

Based on the knowledge that crack formation is strain rate sensitive, it is hypothesized that the formation of micro-splitting cracks and the damage of cement-based matrix in the fiber tunnel are mainly attributing to the rate sensitivity of singly pulled out fibers. Herby, different pull-out mechanisms of straight and mechanically bonded fibers will be examined more closely.

3.1. Hypothesis of matrix failure through end-hooked fibers (H-Fibers)

Although deformed fibers and thus H-fibers are generally considered to be loading rate sensitive during single fiber pull out, the amount of sensitivity is varying in the literature [5,11]. The following hypothesis is provided to explain insignificant [5,11] and significant loading rate sensitivity (in Ref. [11] and in this research) of H-fibers. During H-fiber pull out local pressure is induced into the surrounding matrix near the bending points of the end-hook. In dependency of matrix strength, fiber tensile strength, fiber diameter and end-hook geometry (bending angle) matrix crushing and micro split cracking potentially occur in a localized area. If the fiber pressure leads to an excess of the matrix splitting tensile strength in-plane-split-cracking will potentially occur (Fig. 4). Split cracking has been visually observed by the authors in composite material subjected to direct tension or bending and has also been reported in Ref. [14]. If a large embedment length is used during pull out, such as 12.7 mm in Ref. [11] or 15 mm in Ref. [5], high matrix confinement might be provided counteracting the split cracking, and thus reducing the loading rate sensitivity. Small embedment length, such as 6.35 mm in Ref. [11] or 6.5 mm in Ref. [7], have been used to prevent fiber failure in very high strength matrix and to represent a more statistically relevant embedment length (1/4 of fiber length, length = 30 mm) in a fiber composite. Hereby, the matrix confinement at the crack face is significantly reduced and could lead to in-plane and out-of-plane split cracking (Fig. 4). This could potentially contribute to loading rate sensitivity of hooked fibers with short embedment length. Hence the embedment length of H-fibers influences the rate sensitivity. It is hypothesized that micro split cracking mainly contributes to the loading rate sensitivity of pulled out H-fibers. The amplitude of rate sensitivity depends on matrix strength, matrix confinement (thus embedment length), and fiber strength and geometry.

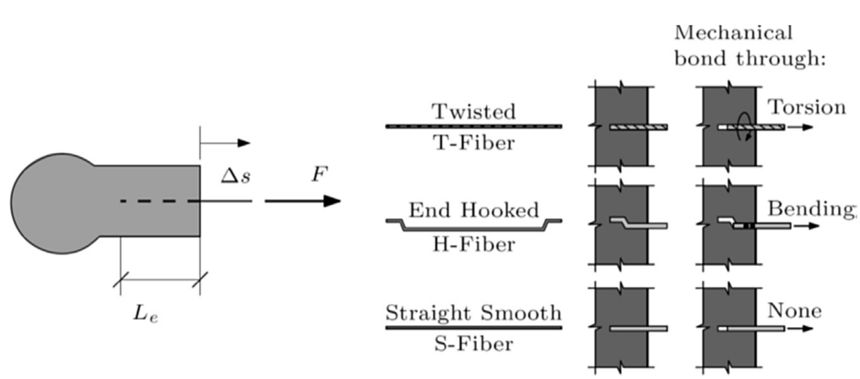

Fig. 1. Pull out mechanisms of straight, end-hooked, and twisted steel fibers.