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Performance of deformed steel fibers embedded in ultra-high performance concrete subjected to various pullout rates

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ABSTRACT

Fiber-matrix bond properties are typically evaluated using a single-fiber pullout test. Such tests for ultra-high performance concrete (UHPC) are few in the literature and, in particular, those that focus on high pullout rates are exceedingly rare. In this research program, different types of high-strength steel fibers (twisted, straight and hooked) are embedded in two UHPC matrices with varying amounts of glass powder, which is a key ingredient of UPHC. The specimens are subjected to loading rates ranging from 0.018 mm/s (representing quasi-static loading) to 1800 mm/s (representing impact loading). Experimental results show that the pullout response of all of the fiber types exhibit progressively increasing rate sensitivity as the pullout speed increases and becomes significant during impact loading. It is most prominent in the smooth and twisted fibers and least in the hooked fibers. Additionally, scanning electron microscope studies are presented and used to explain the mechanism of rate enhancement from a microscopic perspective.

1. Introduction

Ultra High Performance Concrete (UHPC) and its variants, such as Reactive Powder Concrete (RPC), are known to exhibit exceptional mechanical properties [1–12]. The strong performance is attributed to high packing density, which is achieved by carefully controlling the size and distribution of the constituent particles, and incorporating steel fibers. The unique static properties of UHPC have been shown to translate into excellent characteristics under dynamic loading [12–22], although research in this field has been quite limited so far.

Focusing on slower loading rates, Wille et al. [13,14] reported on the strain rate dependent tensile behavior of UHP-FRC with three different fiber volume fractions under four different strain rates ranging from quasi-static (10^{-4} s^{-1}) to seismic (10^{-1} s^{-1}). The tests results showed that the post-cracking tensile strength and the energy absorption capacity of UHP-FRC increased and the specimens maintained strain hardening tensile behavior accompanied by multiple micro-cracks under increasing strain rates. Pyo et al. [15] conducted research on the strain rate ranging from 0.0001 s^{-1} to 0.1 s^{-1} dependent tensile behavior of UHP-FRC with five different types of fibers including straight and twisted fibers with different geometric properties. Their test results showed noticeable rate effects on post-cracking strength and energy absorption capacity. They also showed that the post cracking strength varied linearly with the fiber reinforcing index and energy absorption capacity varies linearly with the product of the fiber length and the reinforcing index.

Going to higher loading rates, Fujikake et al. [16] investigated the tensile behavior of reactive powder concrete under four loading rates of 1×10^{-4}, 2.0×10^{-1}, 2.0×10^{0} and, 5.0×10^{1} (mm/s). Based on their test results, they proposed a rate-dependent bridging law expressing the relationship between tensile stress and crack opening displacement. Millon et al. [17] investigated the tensile strength and fracture energy of ultra-high performance fiber reinforced concrete (UHP-FRC) utilizing a Hopkinson Bar at strain rates up to 160 s^{-1}. They found that UHPC offers a three times greater dynamic tensile strength and a 29 times greater fracture energy compared to conventional concrete. Bragov et al. [18] conducted tests on CARDIFRC with 6% steel fibers in splitting tensile and three-point bending using the modified Hopkinson Bar. The tests results showed that the dynamic split strength is almost twice the quasi-static value at a stress rate of about 3000 GPa/s and the fracture energy increases nearly by an order of magnitude when the deflection rate is 10^2 mm/s.

Although several researchers noted that UHP-FRC has unusual behavior under rapid loading, most of them reported the effects of strain rate (or stress rate) by performing indirect tensile tests [16–20]. Among the few that conducted direct tests, Tran et al. [21] studied the direct tensile response of UHP-FRCs using three types of steel fibers, including twisted, long and short smooth fibers with 1.5% in volume under strain rates ranging from static to 24 s^{-1}. Cadoni et al. [22] investigated the direct tensile mechanical behavior of UHP-FRC at stress rates of 400–1000 GPa/s using a modified split Hopkinson pressure bar test system. The results showed an increase of peak strength with increasing stress rates. However, due to notching of the specimens, multiple cracking was not observed.

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Numerous studies have shown that good interfacial bond properties between fibers and matrix contribute to higher strength as well as toughness under quasi-static conditions. However, only a few research studies have addressed this topic when rate effects are present [23–27]. Gokoz et al. [23] carried out fiber pullout tests under various loading velocities (from 4.2×10^{-2} mm/s to 3.0×10^{3} mm/s) for smooth steel, glass, and polypropylene fibers. The tested results showed that while polypropylene fibers were very sensitive to loading velocity, smooth steel fibers were insensitive to it. They also reported that the post-peak behavior of smooth steel fibers, whose pullout behavior is mainly based on friction, was almost insensitive to loading velocity. Banthia et al. [24] investigated the pullout resistance of three types deformed fibers (hooked, crimped, and I-shaped fibers) embedded in a cement-based matrix. They performed a series of dynamic tests and found that deformed steel fibers embedded in cementitious matrices sustain a higher load under impact than static pullout. In addition, the pullout energy is also greater under impact as long as the fiber pulls out and does not fail.

Kim et al. [25] investigated the effect loading rate on the pullout behavior of two types deformed fibers. They found that hooked fiber showed no appreciable rate sensitivity when pulled out from the three concrete matrices considered in the study, but twisted fibers showed rate sensitivity that was dependent on matrix strength. Abu-Lebdeh et al. [26] investigated the influence of loading rates on the pullout behavior from very high strength concrete. Their results indicated that the increase in pullout rate increases both peak load and total pullout work for all deformed fibers but there was no effect on smooth fibers. Xu et al. [27] conducted research on four types of high strength steel fiber which include two types of straight smooth fibers and two types of deformed fibers embedded in UHPC. Four different pullout loading rates were applied ranging from 0.025 mm/s to 25 mm/s. The results indicated that hooked fibers exhibited the highest loading rate dependence with respect to maximum pullout load. The twisted fibers revealed the strongest loading rate dependence with respect to pullout energy.

The research reported herein is motivated by the extremely limited set of available experimental data on the role of fibers in enhancing the dynamic response characteristics of UHPC, especially at high pullout rates. As such, the objective of this work is to evaluate the effect of loading rate on the pullout behavior of various types of steel fibers embedded in UHPC. The primary experimental variables are fiber type (straight smooth, hooked, and twisted), fiber diameter, and loading rate. In addition, the influence of reducing the amount of glass powder on fiber pull out behavior is explored, an issue that has not been adequately explored in the past. Glass powder is a key constituent of UHPC, but is expensive, thus providing motivation to reduce or eliminate it from UHPC mixes.

2. Rationale for steel fiber pullout testing

Fiber-matrix interfacial behavior plays a critical role in the overall response of fiber reinforced concretes. In uncracked concretes, stresses are transmitted from the matrix to the fibers through interfacial bond. After the concrete cracks, fibers bridging the crack contribute to the load carrying capacity of the concrete. As such, it is well understood that the tensile behavior of fiber reinforced cementitious composites depends greatly on the pullout response of a single fiber.

Fig. 1, which is adapted from [28], illustrates the typical pullout mechanisms and the induced fiber tensile stress-versus-slip behavior of straight (S), hooked (H) and twisted (T) fibers during pullout from a high-strength cementitious matrix. As a straight fiber is loaded, the tensile stress in it increases until its debonding capacity is exceeded and the fiber slips. Subsequent pullout loading leads to a rapid stress drop as the pullout slip increases. The pullout resistance is controlled by the physicochemical bond properties between the matrix and the fiber. In hooked fibers, the bending resistance of the hooked end induces increasing pressure on the cementitious matrix under increasing pullout load. This increases the frictional force and causes corresponding increases in the pullout resistance. The mechanical contribution decreases with an increase in slip and is effective until the end hook forms plastic hinges and starts to pull out. The twisted fiber provides a mechanical contribution along its embedded length that is activated by untwisting of the fiber [29]. The untwisting causes a torque resistance, which applies a slip-increasing pressure on the cementitious matrix along the fiber length, thereby increasing pullout resistance and the amount of dissipated energy up to very high slip out levels. These pullout mechanisms are well understood [28,29] under pseudo-static loading, but it is not clear if they still dominate behavior under high pullout loading rates.

3. Experimental program

3.1. Materials used in UHPC

Table 1 provides the proportions of the mix components of the ultra-high performance strength (UHPC) investigated in this study. The mix proportions (termed mix M1 in this work) were develop at the University of Michigan and the resulting material has been shown to achieve at least 150 MPa compressive strength without heat treatment [8,10,12]. The constituents are as follows: 1) ASTM Type I Portland cement,

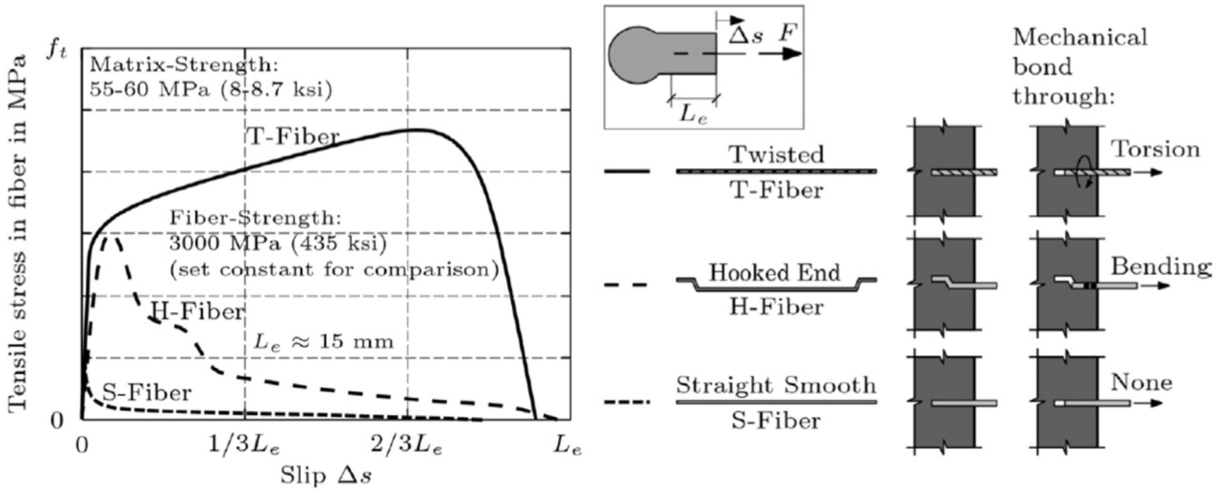

Fig. 1. Illustrated the typical tensile stress-versus-slip behavior of straight (S), hooked (H) and twisted (T) fibers during pullout from a cementitious matrix [28].