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Effect of the fiber geometry on the pullout response of mechanically deformed steel fibers

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ABSTRACT

A simple model to predict the influence of fiber geometry on the pullout of mechanically deformed steel fibers from cementitious matrix is proposed. During the pullout the mechanically deformed fiber is subjected to repetitive bending and unbending which cause an increase of the tension in the fiber. This increase of the tension depends on the amount of plastic work needed to straighten the fiber during pullout. The model input parameters are mechanical and geometrical properties of mechanically deformed fibers. Model predictions were compared to the experimental results on the hooked-end and crimped steel fiber pullout and good agreement was observed.

1. Introduction

Concrete is a brittle material with low ductility. The tensile strain capacity of the concrete is low, and the tensile strength is only about 5% to 10% of its compressive strength. To improve the above mentioned properties of the concrete, FRC (fiber reinforced concrete) has been developed, which is defined as concrete containing dispersed randomly oriented short fibers. The main role of dispersed fibers is to control the crack opening and propagation by bridging the crack faces and providing resistance to crack opening whichever directions the cracks form. The addition of fibers greatly enhances the post-peak structural ductility, a quantity valued by the engineers for safety reasons. Steel fiber is the most common type of fiber used to reinforce concrete.

The bridging action provided by the fibers strongly depends on the pullout mechanism. A pullout test of a single fiber embedded in cementitious matrix can be used to assess the effectiveness of the fiber. Although pullout of straight steel fibers has been extensively analyzed by many researchers [1–12], experiments have shown that in improving the pullout resistance, mechanically deformed fibers are more effective than straight fibers [13–15] due to the mechanical anchorage created by the deformed shape of the fiber. While the fiber/matrix debonding and frictional sliding are the two main mechanisms controlling the pullout of straight fibers, additional mechanism due to fiber straightening during pullout must be taken into account for mechanically deformed fibers, which introduces additional complexity on the pullout response.

There are few attempts to model the effect of fiber geometry on pullout of steel fibers [16–20]. Chanvillard [16] proposed a model which accounts for fiber deformation during pullout requiring a numerical integration procedure to obtain the pullout load–displacement curve. Alwan et al. [17] developed a frictional pulley model to predict the pullout force of hooked-end steel fibers. Sujivorakul et al. [18] extended the straight fiber pullout model by adding a nonlinear spring at the end of the fiber to model the effect of mechanical anchorage. Georgiadi-Stefanidi et al. [19] developed a three-dimensional and simplified two-dimensional finite element model to simulate the pullout of hooked-end steel fibers. Laranjeira et al. [20] proposed an analytical model to predict the pullout response of inclined hooked-end steel fibers. The effect of the hooked-end was experimentally evaluated by subtracting the pullout curve of aligned straight fiber from the pullout curve of aligned hooked-end fiber.

The objective of this study is to derive a simple analytical model for the effect of fiber geometry on the pullout behavior of steel fibers suitable for practical use. The importance of this research lies in the fact that almost all commercially available steel fibers are mechanically deformed. The model input parameters are mechanical and geometrical properties of deformed fibers. The model is validated against experimental results on the hooked-end and crimped fiber pullout. The results show that the model is able to estimate the pullout load of mechanically deformed fibers with sufficient accuracy.

2. Experimental program

2.1. Materials and specimens

Commercially available hooked-end steel fibers HE 75/50 and HE + 1/60, and crimped steel fibers Tabix + 1/60 produced by ArcelorMittal were used in the pullout tests. Straight fibers were also tested to determine the bond and friction at the fiber/matrix interface. Straight fibers were obtained by cutting the hooked-ends of

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the HE 75/50 and HE + 1/60 fibers. The fiber pullout specimen consisted of a single fiber embedded in a square block of cementitious matrix (see Fig. 1). The edge length of the block was 70 mm. The fiber embedment length of H was 15 mm (HE + 1/60 and Tabix + 1/60 fibers), 25 mm (HE 75/50 fibers) and 30 mm (HE + 1/60 and Tabix + 1/60 fibers).

To make pullout specimens, water/cement ratio of 0.5 was employed. The maximum aggregate size was 8 mm. Specimens were cast in plywood molds. Oil was applied to the interior surfaces of the molds to allow easy removal of the specimens from the molds. After the casting, the molds were covered with a thin polyethylene film and left for 48 h at room temperature. Then specimens were carefully removed from the molds and put into a water bath for further curing. After 28 days the pullout tests were carried out. The compressive strength of the cementitious matrix was determined from three cubic specimens with an edge length of 150 mm. The average compressive strength at the age of the fiber pullout tests was 39 MPa. Fibers were pulled out under displacement control with a loading rate of 0.5 mm/min.

Geometry of crimped steel fiber is shown in Fig. 2. The fiber geometry is considered as being composed of straight segment of length l_e and periodically repeating curved segments of length $\rho\theta$ and straight segments of length l. Hooked-end fiber is a special case of crimped fiber, where hook's geometry is composed of only two curved segments of length $\rho\theta$ and two straight segments of lengths l_e and l. The properties of the steel fibers are summarized in Table 1. The geometric parameters (r, l_e, l, ρ, θ) exhibited in Table 1 were obtained by measuring specific fibers. The yield stress of steel fiber σ_Y was taken from the datasheets supplied by ArcelorMittal.

2.2. Results of pullout testing

Experimental pullout curves of straight steel fibers are shown in Fig. 3. After the peak load value was reached, a rapid decrease of the pullout load was observed, which corresponds to a sudden increase of damage at the fiber/matrix interface. Afterwards the pullout load nearly linearly approached to zero. After debonding the pullout load is determined by the friction between the fiber and matrix.

Pullout response of hooked-end steel fibers is shown in Fig. 4. Straightening of the hooked-end and subsequent fiber pullout under frictional resistance was observed for both embedment lengths.

Pullout curves of crimped steel fibers are shown in Fig. 5. All crimped fibers with embedment length of 30 mm failed by fiber rupture. Pullout was only observed for crimped fibers with embedment length of 15 mm. The embedded parts of the hooked-end and crimped steel fibers were subjected to plastic deformations, which led to a substantial increase of the pullout resistance.

Fig. 1. Single fiber pullout specimens.

3. Proposed model

3.1. Frictional sliding of fiber through straight matrix duct

After the fiber has fully debonded, the pullout load P of mechanically deformed fiber can be split into two components:

$$P = P_{pl} + P_{fric} \tag{1}$$

where P_{pl} is the component due to the plastic bending of the fiber in the curved matrix ducts and P_{fric} is the component due to the frictional sliding of fiber through the straight matrix ducts. To calculate P_{fric} one must determine the frictional shear stress τ. The frictional shear stress can be obtained if the pullout load of straight fiber after debonding P_s and the corresponding fiber slip Δ are known:

$$\tau = \frac{P_s}{2\pi r(H-\Delta)}. \tag{2}$$

Fig. 6 shows averaged dependence of the frictional shear stress on the fiber slip obtained from straight fiber pullout tests (see Fig. 3). During the pullout process the frictional shear stress rapidly decreases and then remains approximately constant at a value of about 0.82 MPa.

3.2. Bending of fiber under tension

During the pullout the mechanically deformed fiber is subjected to repetitive elastoplastic bending and unbending which cause an increase of the tension in the fiber. In order to calculate P_{pl} change of the tension in the fiber due to bending must be determined. The following assumptions are made:

1. The material is isotropic and strain-rate independent.
2. The Bauschinger effect is neglected during the bending and unbending.
3. The elastic strains are small in comparison with the plastic strains and can be neglected. Hence, the material is assumed to be rigid, perfectly plastic.
4. The damage of cementitious matrix around the mechanically deformed fiber during the pullout is neglected.

If the fiber is subjected to a tension force less than the yield tension $T_Y = \pi r^2 \sigma_Y$ and then to a moment sufficient to generate some curvature ρ, then the strain and stress distributions will be as in Fig. 7. The neutral surface will be at some distance e from the mid-surface. The strain in Fig. 7 is:

$$\varepsilon_1 = \frac{e}{\rho} + \frac{x_2}{\rho}. \tag{3}$$

The stress in Fig. 7 is:

$$\sigma_1 = \begin{cases} \sigma_Y, x_2 > -e \\ -\sigma_Y, x_2 < -e \end{cases}. \tag{4}$$

The fiber tension T can be expressed as:

$$T = \int_{S^-} -\sigma_Y dS + \int_{S^+} \sigma_Y dS = 2\sigma_Y \left(e\sqrt{r^2 - e^2} + r^2 \sin^{-1}\left(\frac{e}{r}\right)\right) \tag{5}$$

or

$$\frac{T}{T_Y} = \frac{2}{\pi}\left(\frac{e}{r}\sqrt{1-\left(\frac{e}{r}\right)^2} + \sin^{-1}\left(\frac{e}{r}\right)\right). \tag{6}$$

To check the rigid, perfectly plastic assumption, let us assume that the fiber material is elastic, perfectly plastic. Then distance y_e from the neutral axis at which the stress reaches σ_Y is $y_e = \rho\sigma_Y/E$, where E is the elastic modulus of fiber. If $y_e/r \ll 1$ then one can use the rigid,