NUMERICAL STUDY ON SINGLE FIBER PULL-OUT TEST FOR FIBER REINFORCED CONCRETE

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Abstract

The effect of interface modulus and strength on properties of steel fiber reinforced concrete (SFRC) and the stress transferring procedure through interface have been studied on meso-level in this paper by conducting numerical simulation on fiber pullout test. Both mechanical properties of interface and stress transferring behavior are crucial to the overall mechanical properties of the whole composite. Interface stress behavior, mechanism of the fiber reinforcement, toughness and failure-resistance have been analyzed and discussed. Furthermore, characteristics and patterns of stresses near the interface have also been investigated. The shear stress distribution has been found asymmetric when load applied. In addition, the effect of embedding depth of fiber has also been studied.

1 Introduction

SFRC is a typical composite material used in engineering. The failure model of SFRC under tension load is that major fibers would be pulled out however without broken [1], which actually implies that there is space to increase the strength of SFRC. Stress in SFRC could transfer through interface between the fiber and the matrix of concrete, the properties of interface and the stress transferring procedure are, therefore, crucial to the properties of the composite as a whole. Many researchers have great interest in this field [2]. Back to early 1950s, most modeling and theoretical works on interface are based on a so-called shear lag model [3~4]. After that, many improved models had been proposed, however in most models, the bond of interface is assumed unbroken and homogeneous, which is not true. Actually, SFRC is well known as a typical heterogenic composite.

To measure the damage and failure of interface of SFRC by experiment is one of the important work contents, and the pullout test of single fiber proposed by Broutman [5] had been widely used because of its simplicity and lower cost. However, the interpretations on the test results are based on a traditional and simplified theory, for example, shear stress was assumed evenly distributed along the fiber in most of them. The interface shear stress can then be estimated, however not actually correct. Moreover, the development of cracks during the pullout test is more complicated, so the detailed mechanism of interface failure is far from understood[6~9].

Along with rapid development of modern computational methods, numerical simulation on pullout test has become an important tool by adopting FEM etc. A series of valuable findings can be identified in papers [10~13]. Most of such studies are also based on the assumption of homogenous materials and axial symmetrical models. These assumptions and models cannot match the typical heterogeneity of SFRC. Furthermore, in most studies, the effect of aggregates has seldom been considered, so the concrete matrix is often treated as cement matrix actually.

In this paper, couple interaction among steel fibers, concrete, aggregates and interface between steel fiber and the concrete have been investigated. Properties of SFRC as a whole and toughening mechanism of SFRC can then be studied by carrying out numerical simulation on the pullout of the steel fiber, with different interface properties and different embedding depth.

2 Numerical Modeling

A fiber pullout model is shown in *Figure 1*, with a dimension 20 x 30 mm. The model contains 200x300=60,000 cells. Four kinds of materials have been considered in the model to simulate steel fibers, concrete, aggregates and interface between fibers and concrete, respectively. The properties of the first three materials are summarized in Table 1. Varied strength and modulus of interface and the embedding depth of steel fiber have been applied in the simulation so their effects on pullout procedure and the overall macro properties could be investigated. The vertical load has been applied by controlling the displacement of the upper end of the fiber with a step of 1.0E-5 mm.

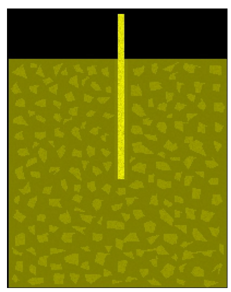


Figure 1. Model of fiber pullout test

Material	Modulus [MPa]	Tension Strength [MPa]	Poisson's Ratio
Concrete Matrix	8000(5)	1.5(5)	0.2(100)
Steel Fibers	200000(10)	400(10)	0.25(100)
Aggregate	30000(5)	30(5)	0.20(100)

Notes: Figures in brackets are index of homogeneity, the larger the figure is, more homogeneous the corresponding material property is.

Table 1. Summary of Properties of the Model

To describe the actual heterogenic distribution of mechanical properties of material, it is assumed that the heterogeneity of material is with Weibull function, which is shown in *Equation 1* below and could also be referred to Tang [14]:

$$\varphi(\alpha) = \frac{m}{\alpha_0} \cdot \left(\frac{\alpha}{\alpha_0}\right)^{m-1} \cdot e^{-\left(\frac{\alpha}{\alpha_0}\right)^m} \tag{1}$$

where α stands for mechanical characteristic parameters, like elastic modulus, strength, Poisson's ratio etc. α_0 is the mean value of α. m is the shape factor of Weibull, defined as homogeneity index of material. $\varphi(\alpha)$ is the so-called probability density function (PDF).

Each meso-level cell is initialized as elastic, when the stress of the cell increases, damage could happen if a pre-set damage criterion (either stress or strain) is met. In this study, modified Coulomb criterion of ceiling of tension stress has been adopted, which could be described as: a) maximum tensile stress principle, i.e. the damage will occur when the stress exceeds the allowable tensile stress (*Equation 2*); and b) Moor-Coulomb criterion, i.e. shear damage could happen when the stress field touches the Moor Coulomb circle (see *Equation 3*).

$$\sigma_1 \geq \sigma_t \tag{2}$$

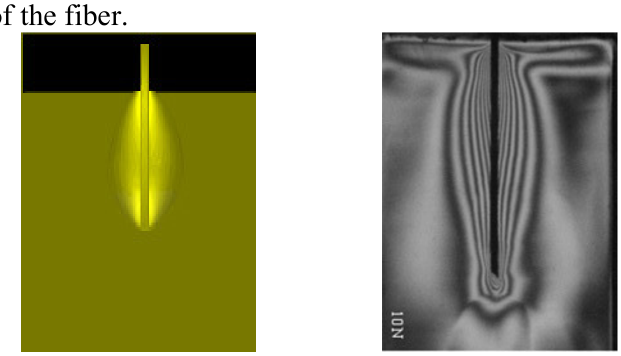
and/or

$$\frac{1+\sin\phi}{1-\sin\phi}\sigma_1 - \sigma_3 \geq \sigma_c \tag{3}$$

where ϕ is the frictional angle. σ_1 and σ_3 are the maximum and minimum principal stresses, respectively. σ_t and σ_c are the uniaxial tensile and compression strength of a unit cell, respectively.

3 Results & Discussions

The results of numerical simulation by using RFPA in this study and the photo elastic tests on fiber pull out models, carried out by Zhao [15] have been presented in *Figure 2a and 2b*, respectively. Both the numerical and the experimental results show that the shear stresses do not distribute evenly in the axial direction. Stress concentration phenomenon can be obviously observed near the embedding end and the tip of the fiber. The maximum stress appears near the embedding end of the fiber.



a: Simulation of RFPA b: Photo Elastic Test [15]

Figure 2. Shear Stress Picture

The effect of interface strength, elastic modulus and the embedding depth on the pull out test and the overall macro properties will be discussed in following sections.

3.1 The effect of interface strength on pullout property of single fiber

In this group of samples, the interface strength (F_i) had been set to be 1%, 3%, 6% and 10% of fiber strength (F_f), respectively, while keeping other parameters of interface as constant. In *Figure 3*, the complete load displacement curves of all this four samples have been provided. Experimental results [16-17] show that the pullout procedure can be divided into three stages, which are complete elastic restraint, local split off and complete split off. The corresponding stages on the curves could be summarized as linear elastic, drop down and shift segments. These segments can be identified in all samples but to each sample, the segments are different in features. All elastic segments are almost coincided, because the volume fraction of interface is small, so the variation of interface properties has little effect on this stage. In other words, the properties of the fiber and matrix concrete and their volume fraction dominate the overall properties of SFRC.

The split off and cut-through of interface are determined by the interface strength, so the interface strength has great effect on the peak strength of SFRC and the degradation stage after the peak strength is passed. The peak strength of the sample with weak interface ($F_i /F_f =1\%$) is relatively small, but its toughness is high. Some ductile features appear in the local split off stage. In the degradation stage, the curve is in shape of stairs. For the sample with strong interface ($F_i /F_f =10\%$, its peak strength is high bit lower toughness. An obvious vertical drop down of load appears right after the peak load. Instant failure happens and the sample loses its loading capacity. It shows that in local split off stage it is a typical brittle failure.

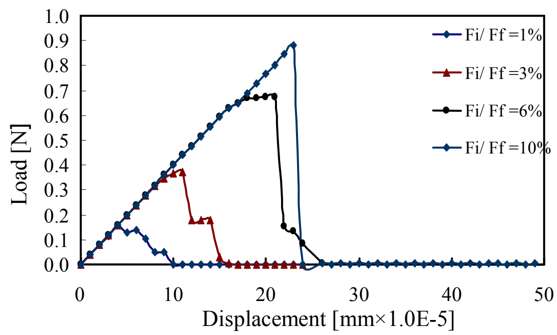


Figure 3. Complete Load-displacement curve with varied interface strength

The peak load and toughness of the above samples are summarized in *Table 2*. (Toughness is defined as the area enveloped by the curve in this paper.) From the table it could be concluded that for samples with moderate interface strength ($F_i /F_f =3\%$ *or* 6%), both strength and toughness can be improved with a balance and the overall properties of SFRC can be optimized. Similar results can be verified in pullout experiments for glass fibers in matrix of epoxy resin, carried out by Sun [18].

Interface Strength	Peak Load [N]	Toughness [N.mm x 1E-5]
F_i/F_f=1%	0.160	0.865
F_i/F_f=3%	0.370	3.100
F_i/F_f=6%	0.675	9.110
F_i/F_f=10%	0.882	10.770

Table 2. Peak load and toughness values corresponding to varied interface strength

The whole procedure of both the weak interface sample ($F_i /F_f=1\%$) and the one with strong interface ($F_i /F_f=10\%$) are presented in *Figure 4a and 4b*, respectively. The micro broken of cells near interface, development of cracks, cut thorough until the fiber complete split off from the matrix could be observed perfectly, though only four failure pictures have been presented in this paper for each sample due to limited pages. From *Figure 4a*, it could be identified that, at the first stage, some weak cells in the stress concentration zones near the bottom and the tip of the fiber would be damaged, and local split-off could then occur right to the bottom of the fiber. Cracks continue to develop and finally the cut-thorough crack is formed in the right area. The cracks around the tip of the fiber develop upwards along the left side of the fiber, which finally, lead to a split off for the entire interface. The fiber is completely pullout from the matrix. Form the damage route, the split-off procedure of the fiber is observed as asymmetric. On the other hand, from *Figure 4b*, the damage procedure shows that the interface cells damage first in the area near the bottom and the tip of the fiber, similar to the case discussed above. However, after the right cut-thorough is formed, the cracks did not develop along the left side of the fiber, because the strength of interface here is high. The crack them deflect to the relevant weak zones alongside the aggregates in the concrete matrix and keep developing along with the applied load until the sample is totally broken.

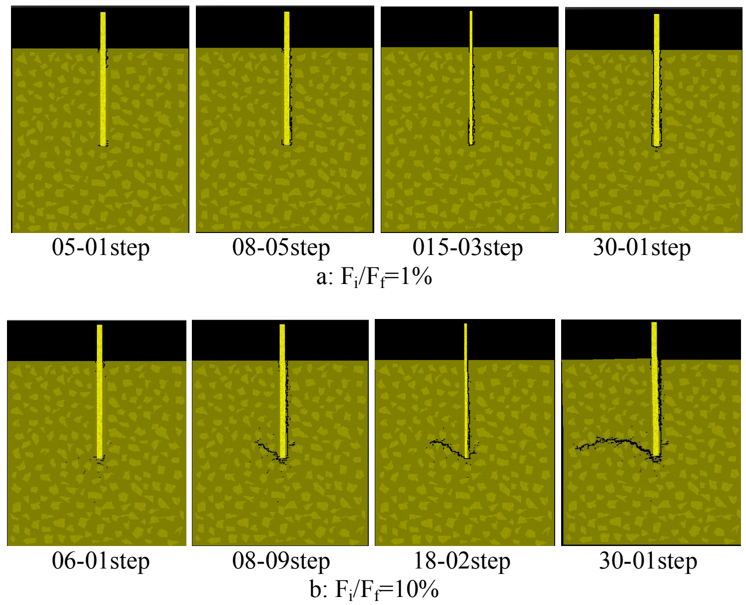


Figure 4. Failure Procedure of samples with weak and strong interface, respectively

3.2 The effect of Interface Modulus

To understand how the modulus of interface affects the overall properties and the toughening mechanism, five samples with E_i/E_f (interface modulus over modulus of SFRC) of 2%, 5%, 10%, 20% and 40% have been prepared, while other parameters were kept unchanged.

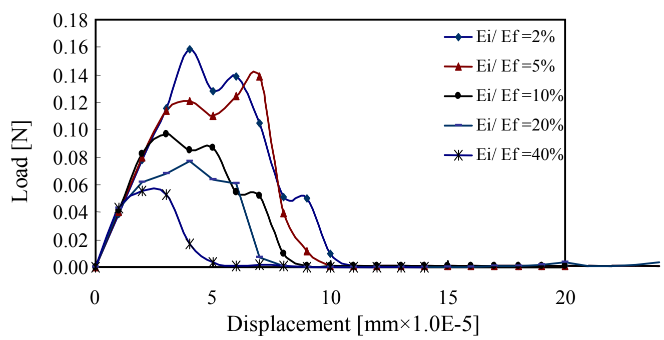


Figure 5. Complete Load-displacement curves with varied interface modulus

The complete load-displacement curves for all five samples in this group are presented in *Figure 5*. Firstly, same as the previous section, at the elastic stage, the lines are coincided, which implies that the change of interface modulus has little effects on the overall properties of SFRC. However, for the peak strength and the degradation stage, interface modulus has great effects. With keeping other parameters unchanged, the sample has both higher peak strength and toughness when the modulus is lower. Liu *et. al.* [19] studied mechanism of long fibers on brittle matrix in 2008. The conclusions they made is same as the above.

The peak load and toughness of the above samples are summarized in *Table 3*. It could see from the table that the peak load and toughness for the sample with E_i/E_f=2% are 1.857 and

3.726 times the corresponding amount of the sample with *E_i/E_f=40%*. Hence, in optimization and production of these kinds of composites, flexible interface is recommended to improve both strength and toughness.

Interface Strength	Peak Load [N]	Toughness [N.mm x 1E-5]
E_i/E_f=2%	0.160	0.865
E_i/E_f=5%	0.140	0.790
E_i/E_f=10%	0.097	0.510
E_i/E_f=20%	0.077	0.460
E_i/E_f=40%	0.056	0.183

Table 3. Peak load and toughness values corresponding to varied interface modulus

3.3 The effect of fiber embedding depth

The failure procedure of three samples with fiber embedding depth set to be 6, 8 and 10mm, respectively, has been simulated to investigate the effect of interface length, which is controlled by the fiber embedding depth, on the overall properties of SFRC. In this group of samples, F_i/F_f and E_i/E_f are set to be 1% and 10%, respectively.

The curves of shear stress distributed along the fiber with different fiber embedding depth, are presented in *Figure 6*. It could be seen that the maximum shear stress appears always near the embedding end of the fiber (the amount is 0.245, 0.195 and 0.155MPa corresponding to samples with embedding depth of 10, 8 and 6mm, respectively). The shear stress drops quickly along the fiber direction and has kept in level of 0.1 MPa with small fluctuation. Finally, near the fiber tip the shear stress increases again, to a level less than the maximum. Generally, stress concentration areas are found closed to both the embedding end and the tip of the fiber. Actually, these results could be verified in FEM analysis and photo elastic experiments carried out by Wang [2] and the pullout test of synthetic fiber from concrete carried out by Li [17].

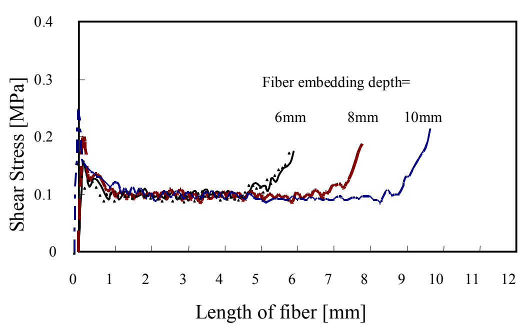


Figure 6. Shear stress distribution along the interface

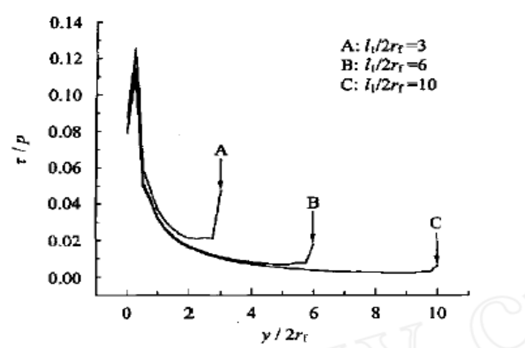


Figure 7. Shear stress distribution along the Interface, simulated by using ANSYS [20]

A similar study on the fiber pullout test was conducted by Peng *et. al.*[20]. In their study, the material was assumed as ideal homogenous and the shear stress along the interface can be obtained by using ANSYS (see *Figure 7*). It is noted the curve in *Figure 7* is smooth because of the homogenous assumption, while in *Figure 6*; the shear stress curve is almost random fluctuated, which actually presents the real condition of stress fields.

A split off procedure of a single fiber pullout with embedding depth of 6mm is shown in *Figure 8*. With increasing external load, the weak cells in the stress concentration area, near both the embedding end and the tip of the fiber, may damage firstly, then the cracks keep develop along the fiber until the tip is met.

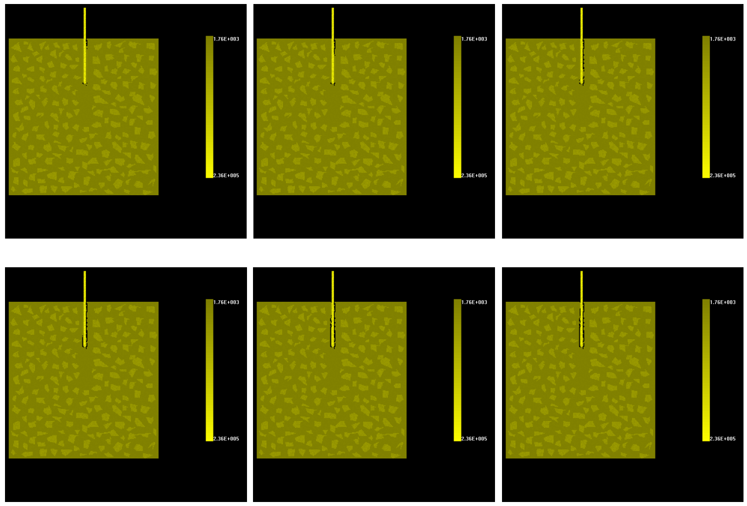


Figure 8. Split off procedure of a sample with embedding depth of 6mm

The complete curves of load and displacement for samples with embedding depth of 10, 8 and 6 mm are presented in *Figure 9*. Within the studying range of the fiber length, the peak load increases when the embedding depth increases. Similar trends can also be found on pullout test of large diameter synthetic fibers and matrix of cement [21].

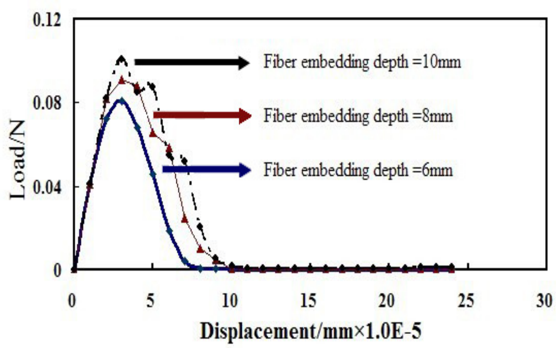


Figure 9. Complete Load-displacement curve with varied embedding depth

4 Conclusions

Based on meso-level, and in consideration of heterogeneity of material cells, the following conclusions can be drawn by numerical simulating pullout test on steel fiber reinforced concrete.

a. The pullout procedure could be divided into three stages, which are complete elastic restraint, local split off and complete split off. In addition, the split off procedure is asymmetric.
b. The higher the interface strength, the higher the peak strength of the sample, and the more brittle the sample is in property. To balance the strength and toughness of the material, using appropriate interface strength is more crucial.
c. If other parameters are kept unchanged, the less the interface modulus, the higher peak strength and the higher toughness the sample could have.
d. The maximum shear stress appears in the embedding end of the fiber. The shear stress decreases quickly along the fiber direction and then increases again near the tip of the fiber. The distribution curve is not smooth because of the assumption of heterogeneity into material.

Acknowledgements

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