ELASTO-PLASTIC SINGLE FIBER PULLING OUT OF MATRIX WITH FRICTION

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Abstract

Fibers are bridging cracks in short fiber brittle matrix composites. Post cracking composite material load –bearing capacity is dependent on each single fiber pull-out process. Numerical modeling results for single elasto-plastic fiber, is pulling out of elastic matrix, are presenting in the paper. Numerical results were compared with the data for single steel fiber pull-out of concrete matrix. 2D elastic and 3D elasto-plastic modeling, using the finite element method (FEM) approach, taking into account friction between fiber and matrix is presenting. Numerical modeling was performed for straight shape fiber was embedded into elastic matrix under variable angles to direction of applied pulling force. Fibers were embedded into matrix at variable depth. Friction between fiber and matrix and matrix shrinkage as well as elastic and plastic deformations in fiber are under investigation.

1. Introduction

Concrete is brittle material with a relatively low tensile strength. Due to this fact, concrete tends to crack. It has been proven by many researchers that the overall behavior of concrete can be improved by the addition of fibers. A wide range of fibers is used for reinforcing concrete (steel, plastic, glass, micro-composite, etc.). Traditional concrete mixing, transportation and casting technologies are used for concretes with dispersed short fibers, with fibers content not exceeding few percent of volume fraction. The positive effect of the fibers, in this situation, is not obvious until the first crack occurs in the concrete. After this point, the behavior of fiber reinforced concrete is different from that of unreinforced. Increasing the applied external loads the matrix fracture process is initializing, micro-cracks start to open to grow and to coalescent finally forming one or few macro-cracks. Fibers are bridging an every macro-crack. Single fiber pull-out micromechanics is governing macro crack opening process. Focusing on micro-mechanical investigations of single fiber pulling out process of elastic matrix is necessary to mention some works. In [1, 2] numerical modeling was performed simulating the pull-out of straight fiber out of a concrete. In [3] was observed the FEM model is approximating the non-linear behaviour of fiber and matrix. In [4-6] detailed 2d and 3d FEM modeling were performed investigating stress distribution in matrix and fiber during pull out process. Interpretations of interface bond micro-mechanical properties were done in [7-9]. Analytical solution for single fiber pulling out of elastic matrix with friction, in orthogonal direction to elastic volume outer surface, was obtained in [10]. Some additional works, have studied behavior of fiber reinforced concrete as well as micro-mechanical parameters that affect a steel fiber pulling out concrete process, are [11-15].

2. Single fiber pull-out micro-mechanics

2.1 Experimental data

Single steel fiber-concrete samples were prepared and were tested in order to determine fiber pull-out resistance experimentally [16-18], different geometry fibers were investigated. Fiber length for all fiber types was 50 mm. For each type of fiber, five different embedded lengths have been observed in the investigation – 25 mm (symmetrical embedding of 50 mm long fiber), 20 mm, 15 mm, 10 mm and 5 mm. In the framework of present investigation, experimental data of pull-out resistance for inclined at different angle to applied pulling out force direction and the effect of embedded fiber length for straight round cross-section steel fibers was used for comparison with numerical modeling data. Experimentally for each configuration of fiber matrix alignment a total number of 9 samples were fabricated thus ensuring adequate statistics of the performed tests.

Analysis of experimentally obtained applied force-pulled out displacement curves leads to conclusion, that different steel fiber shapes involve different micro-mechanisms in the pull-out process. Initially fibers and the surrounding concrete matrix are deforming elastically. The linear elastic behavior of the fiber-matrix system is interrupted by interface debonding which occurs due to overall weak bonding between the concrete matrix and the surface of the steel fiber. Interface shear crack propagates and the interface debonding continues until whole length of the fiber has separated from the surrounding concrete matrix. At that point the further applied pull-out load is resisted only by friction forces resulting from fiber sliding out of the concrete matrix. If steel fiber has inclined to applied tension direction, much of the pull-out resistance can be achieved from its elasto-plastical straightening. Straightening of steel fibers can only be possible if the surrounding concrete matrix has sufficiently enough strength to resist stress concentration at fiber edges. If surrounding concrete matrix is weak, the stress concentration causes failure of the brittle matrix and no pull-out resistance is obtained.

2.2 Stress fields modeling in elastic fiber and elastic matrix

Let start with the situation when elastic single fiber is oriented orthogonal to elastic volume (concrete) surface and is pulling out. External load is applied to fiber pulling it out of matrix. Performed analysis of experimental data for glass and carbon fibers [4-6] was shown four main stages of such process: a) fiber and matrix are bonded together, all deformations in system are elastic; b) cylindrical delamination crack is starting from the outer elastic volume surface propagating between fiber and matrix; c) delamination is reaching all length of fiber after that fiber with friction is pulling out. All mentioned stages were numerically simulated (2D and 3D) using FEM program ANSYS in [4, 6]. Fibers are crossing cracks surfaces in concrete under different angles, this is why is necessary to investigate pull-out micromechanics for inclined to tensile force fibers. 2D numerical simulations were performed using ANSYS FEM software for single fiber pulled out of elastic volume under an angle $\alpha \in [0^o, 80^o]$ to fiber's embedment direction, according models: with perfect bond between concrete and fiber; with partial debonding and sliding. Delamination started and for inclined fiber in concrete with partial debonding overloads are going inside the concrete block (similarly like for straight fiber). Fiber sliding tends to originate micro-cracks in concrete around empty fiber channel in concrete. Performed numerical simulations were shown possibility to realize numerous failure micro-mechanical mechanisms for single elastic fiber pulling out of elastic matrix. At the same time is important to conclude that elastic analysis is unable to describe micro-mechanics of metal (steel) fibers pulling out of concrete matrix, which are deforming elasto-plastically, as well as, more precise friction (between fiber and matrix) consideration leads to necessity to use 3D modeling elasto plastic modeling.

2.3 Stress fields modeling in elasto-plastic fiber and elastic matrix

Single straight elasto-plastic fiber is oriented orthogonal to elastic volume (concrete) surface and is pulling out. 3D geometrical model was created using Solid Works FEM software. Fiber is pulling out with friction out of matrix. Matrix shrinkage is taking into account. The problem is solving in the form of contact analysis. The complete pull-out process of fiber is modeling, during which displacement is applied to the loose fiber end. Fiber is debonded and the largest contribution to pull-out resistance is expected to occur from friction, which is magnified by the residual compression. Fiber is sliding with friction and is deforming elasto-plastically. According to symmetry only one forth part of volume was observed. One end of the model volume is rigidly clamped; outer cylindrical surface is under symmetry boundary conditions. Motion boundary conditions has been applied to the fiber loose end surface $u=l_f$. Between the fiber and the matrix were specified no penetration numerical condition and also was applied friction. Was used Coulomb friction model. The results of the numerical model were compared with experimental data for straight steel fibers pull-out having the length 50 mm and diameter 0.75 mm [16-18] with the goal to evaluate importance of such micromechanical processes as fiber's plasticity and fiber- matrix friction. Applied force - pulling fiber's displacement diagrams were numerically obtained and were compared with experimental data. Two parameters in the model were varied with the goal to more preciously approximate experimentally obtained curves: friction coefficient between steel fiber and concrete matrix; and shrinkage of concrete. For macroscopic interaction friction coefficient between steel and concrete is known and is equal to 0, 45. In the model we accepted the same value. The value of shrinkage was chosen by comparing the modeling results and experimental data for straight fiber embedded into matrix on the depth equal to 5 mm. Numerically into the matrix, with empty channel for the fiber, was introduced the fiber having the larger outer diameter than the inner diameter of the channel for the fiber. For example for concrete matrix shrinkage was equal to 0.007.

The fiber was embedded into the matrix on a different depth (L): 5, 10, 15 and 20 mm. Data of performed pull-out experiments are shown in [15-18]. Fibers were embedded on the depth L into concrete straightly orthogonally to concrete volume outer surface and were pulled out in direction coincident with the fiber. Every experimental curve has typical parts. First (starting with pull-out displacement equal to zero and till 0,05-0,15mm) part corresponds to elastic fiber deformation in elastic matrix with perfect bond between fiber and matrix. Curve is a straight line. This part is successfully modeling by developed numerical model. Second part of the curve (starting from 0,05-0,15mm to 0,5-0,6mm on pull-out displacement axis) corresponds to delamination growth along fiber-matrix interface till full fiber debonding and partial motion with friction of its part (close to the loose fiber's end) out of the matrix. Next part of the curve is concerned with fiber sliding with friction out of the matrix and partial plastic fiber deformation for fibers embedded into the matrix at high depth. At the beginning curve is going up, applied force is increasing, after that at experimental curves we can recognize the "Plato" the curve part with practically constant applied pulling out force and growing pull-out displacement. Peaks and dimples on this curve part (like oscillations) can be explained by small concrete particles separation out of internal concrete surface by moving with friction fiber and plugs formation around the fiber out of these particles. Plug in the channel between fiber and matrix is triggering fiber motion increasing resistance to motion. After that plug is failing allowing fiber to move with decreasing applied pulling out load. Small particles in the channel between fiber and matrix are rolling after some time forming next plug (next peak on the curve). This plug formation process is dependent on fiber embedment depth (higher is embedment depth more peaks we see on the experimental curve), concrete matrix granulometry and matrix internal cohesion. Numerical model fail to approximate this part of the curve, because constant friction force was accepted at every two contact surfaces units along fiber and matrix. On the right picture applied pull-out forces are monotonically decreasing because during pull-out process is decreasing every fiber surface is in contact with the matrix, when fiber is coming out of the matrix.

2.4 Modeling in situation when fiber is inclined to pulling out force direction

Single straight elasto-plastic fiber is inclined (oriented under the angle) to tensile pulling out force. Force acting direction is oriented orthogonally to elastic volume (concrete) outer surface. 3D geometrical model was elaborated using Solid Works FEM software (see Fig. 1). Fiber is pulling out of matrix with friction. Matrix shrinkage is taking into account. The problem is solving in the form of contact analysis. The complete pull-out process of fiber is modeling till the moment when whole fiber embedded end is pulled out of matrix. According to symmetry only half of the fiber in matrix was observed. Growing displacement is applied to the loose fiber end. Fiber is debonded. Coming out of elastic matrix fiber is deforming elasto-plastically. Such the contribution in pull-out resistance is forming by friction between

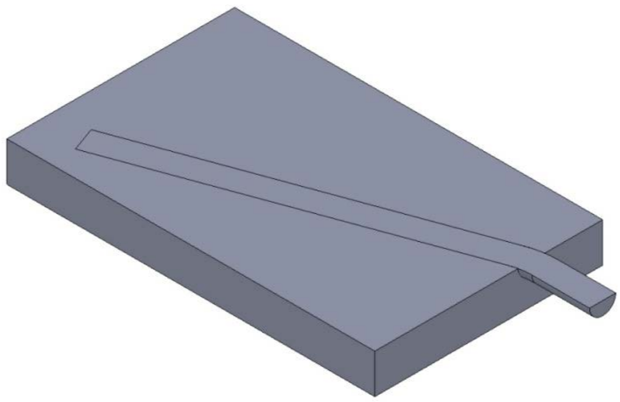

Figure 1. Pull out model for different inclination angles.

fiber and matrix and elasto-plastic fiber bending. Equivalent von Mises stresses distribution in the fiber is shown (if fiber was embedded at 10mm under the angle 20 degrees to pulling out force direction) in figure 2, 3. Equivalent elasto-plastic von Mises stresses distribution in the fiber and in the matrix are shown in figure 3 a, b. Fiber was embedded at 10mm, under 20 degrees to pulling out force direction and is partially pulled out. Overstress location in the matrix corresponds to fiber end location. Elasto-plastic shear stress in the fiber (is embedded at 15 mm into the matrix) is shown in figure 4a and is embedded at 20 mm into the matrix, is shown in figure 4a ( ).
Friction is magnified by the residual compression due to matrix shrinkage. Numerical calculations were performed for steel fiber in concrete matrix (performing fitting procedure according to shrinkage of concrete matrix). Present stress in the fiber is exceeding the yield stress of steel; therefore large displacements study was used for pull out curve modeling. Experimentally were obtain stress-strain curves for fibers embedded at different depth and

were oriented under different angle to applied pulling out force. Standard Solid Works plastical behavior description was used. Experimental and modeling curves for straight rounded steel fibers with the length 50mm and diameter 0,75mm were embedded into the matrix on a depth: 10mm, and oriented under angles: a) -20^0; b) - 45^0 ; c) - 60^0 degrees to applied pulling force are shown in figures 5a,b, 6a. In figures 6b, 7a), 7b) are shown experimental and modeling results for the fiber oriented under the angle 20^0 to pulling out force direction and is partially pulled out.

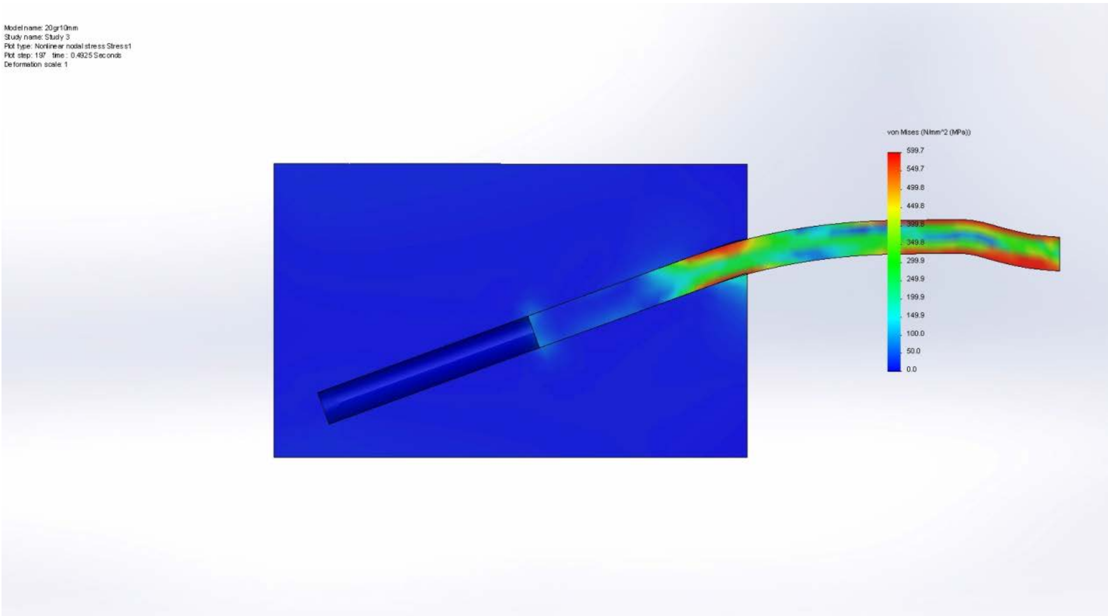

Figure 2. Steel fiber is pulling out of concrete block. Equivalent elasto-plastic von Mises stress distribution in the fiber. Fiber was embedded at 10mm, under 20 degrees to pulling out force direction and is partially pulled out.

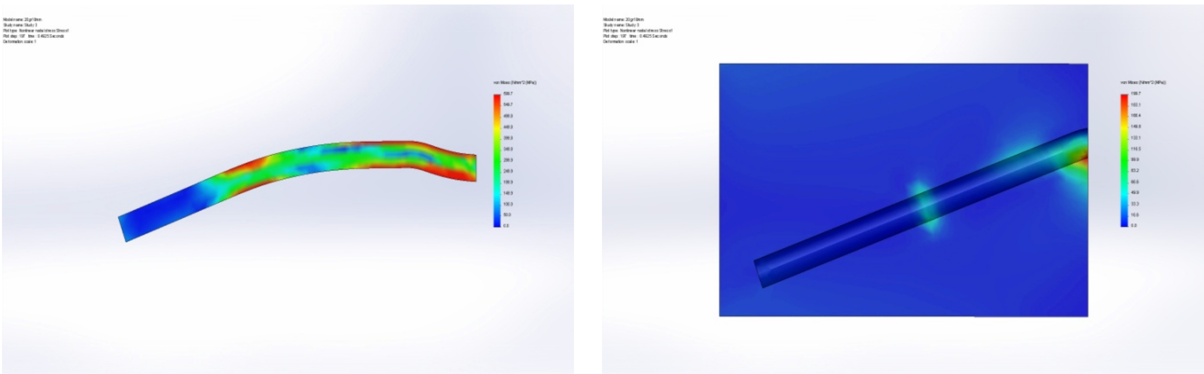

Figure 3. Equivalent elasto-plastic von Mises stress distribution in the fiber (a) and in the matrix (b). Fiber was embedded at 10mm, under 20 degrees to pulling out force direction and is partially pulled out. Overstress location in the matrix corresponds to fiber end location.

Experimental data comparison with numerical modeling results leads to conclusion that implementation of two non-linear processes: fiber-matrix friction and fiber plastical deformation into single fiber pull-out micro-mechanics allows quit correctly predict this process changing its parameters (angle and embedment depth) in wide range. At the same moment, for model improvement, concrete particles plugging process must be included into consideration.

3. Conclusions

Detailed 2D numerical (FEM) investigation for elastic single fiber pull-out of concrete matrix was performed. Simulations results were compared with performed experiments. Main fiber load bearing and rupture mechanisms were recognized. Detailed 3D numerical (FEM) investigation for elasto-plastic single fiber pull-out of concrete matrix was realized.

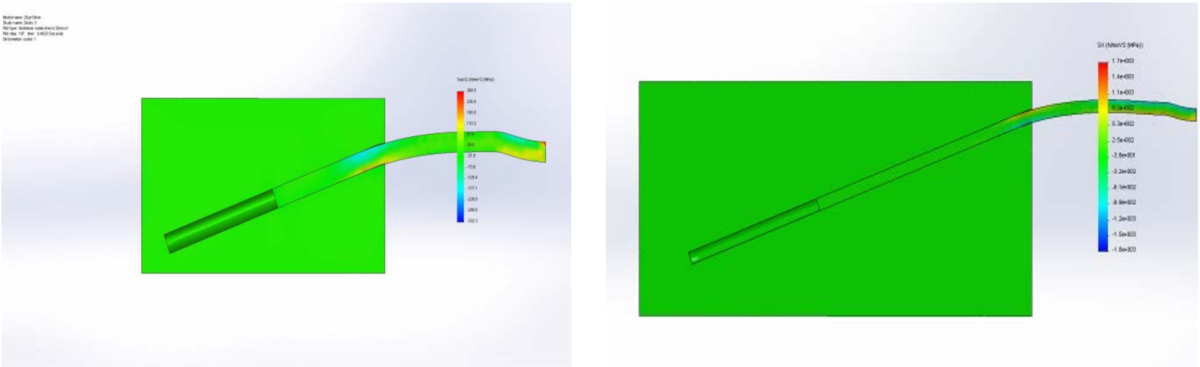

Figure 4. Steel fiber is pulling out of concrete block. (a) elasto-plastic shear stress distribution in the fiber. Fiber was embedded at 10mm under 20 degrees to pulling out force direction and is partially pulled out; (b) elasto-plastic normal stress distribution in the fiber. Fiber was embedded at 20mm under 20 degrees to pulling out force direction and is partially pulled out.

applied force direction and embedded at different depth into matrix. Comparing experimental

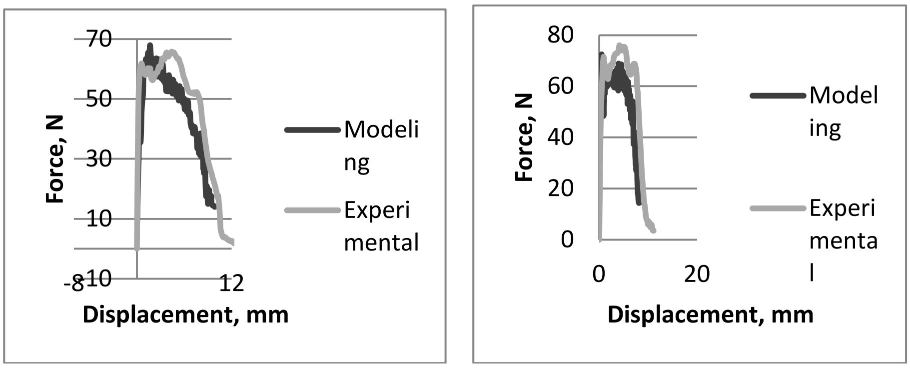

Figure 5. Experimental and modeling curves for fibers were embedded into the matrix on a depth 10mm. a) Fiber is oriented under the angle 20^0 to applied force direction; b) Fiber is oriented under the angle 45^0 to applied force direction.

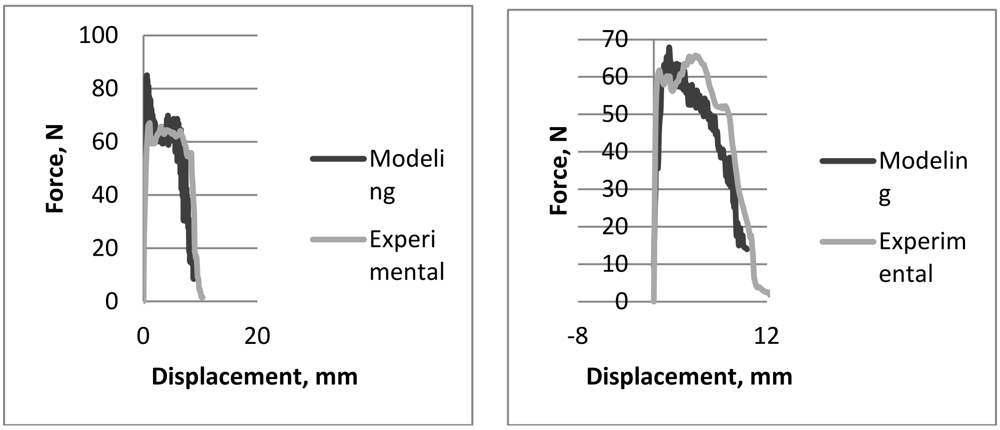

Figure 6. Experimental and modeling curves for fibers were embedded into the matrix on a depth 10mm. a) Fiber is oriented under the angle $60^0$to applied force direction; b) Fiber is oriented under the angle $20^0$to applied force direction and is embedded into the matrix on a depth 15mm.

Simulations results were compared with experiments. Was shown that model based on assumptions about friction between fiber and matrix and elastic fiber and matrix deformations fail to predict experimentally obtained curves. Micro-mechanical mechanism of small concrete particles separation out of internal fiber channel surface in concrete because fiber friction and plugs formation around the fiber must be taken into account. Plug in the channel between fiber and matrix is triggering fiber motion increasing resistance to motion. After that plug is failing, allowing fiber to move simultaneously decreasing applied pulling load. Small particles in the channel between fiber and matrix are rolling after some time forming next

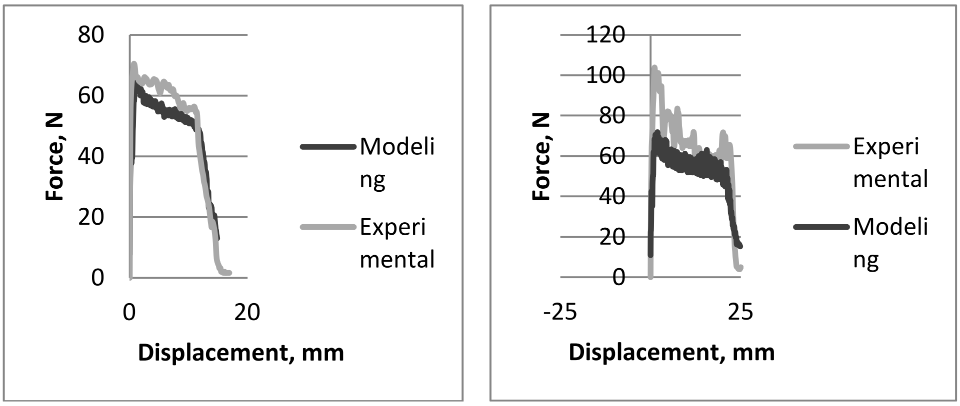

Figure 7. Experimental and modeling curves for fibers were oriented under the angle 20^0 to applied force direction. a) Fiber is embedded into the matrix on a depth 20 mm; b) Fiber is embedded into the matrix on a depth 25 mm.

plug. Numerical simulations were shown that in situation, when fiber is inclined to acting force direction, this plugging process importance is decreasing in comparison with other non-linear acting processes –friction and plastical deformations.

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