Experimental and numerical investigation of steel fiber reinforced concrete fracture

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Abstract. In this work a two-scale model for the fiber-reinforced concrete is presented. The model uses pull-out forces of individual fibers and fibers distribution obtained from experiment or micro mechanical models and incorporates them in discrete way into finite element model of concrete matrix. The matrix behavior is described using cohesive zone model and influence of individual fibers is introduced into model as reaction forces acting on the nodes of the background mesh.

Introduction

The fracture of fiber reinforced concrete is complex phenomenon occurring at different length scales. Different models were proposed in the last years for the prediction of the fracture process of fiber reinforced concrete. One of the most common approaches is cohesive zone model where the traction-separation law for the fiber-reinforced concrete is derived by averaging the pull-out forces of all fibers crossing the fracture plane [1]. Such models work well for sufficiently homogeneous distribution of fibers. However, averaging procedure may introduce error in flexural response of concrete prediction in cases with highly non-uniform distribution of fibers. More complex models with discrete fibers may be necessary in such cases. Only few such models were developed recently. The 2D and 3D lattice model with cement matrix, aggregates and discrete steel fibers was used in [2] to simulate the fracture behavior of fiber-reinforced concrete. In [3] the 3D smeared crack model was used to model concrete cracking and the truss elements were used to model the bridging action of steel fibers. In [4] the damage model was used to model the matrix material and the steel fibers were indirectly modeled as traction forces mapped to the neighbor nodes of the background mesh. In this approach the mesh refinement around fibers is not necessary and the total number of degrees of freedom in the system remains unchanged.

In current work a numerical model is developed based on finite element analysis and cohesive zone approach for the concrete matrix that allows simulating crack growth without explicit modeling of predefined crack path. And the bridging action of the reinforcing fibers is indirectly modeled as traction forces mapped to the nodes of elements that crosses the fiber.

Experimental

Pull-out test. Pull-out tests of steel fibers with "hook-ends" (HE+ 1/60) embedded in concrete block at different angles were performed to estimate force-displacement relationships. The length of the fibers is 60 mm and diameter – 1 mm. Results of the pull-out forces for fibers with 4 inclination angles (0, 20, 40 and 60 degrees) embedded in concrete block at depth 30 mm are presented in Fig. 1. Previous studies of the pull-out tests for fibers with "hook-end" suggest that embedded depth of the fiber has relatively small effect on the pull-out force [5, 6].

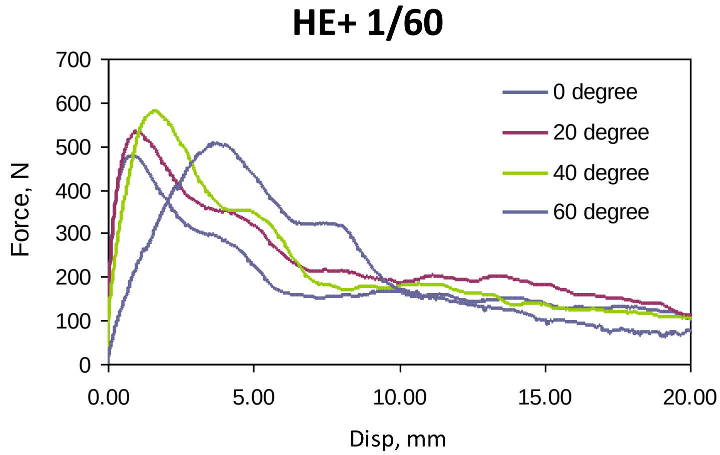


Fig. 1 Pull-out behavior of HE+ 1/60 hook-end steel fibers embedded at different angles.

Orientation of the fibers. It is well known that fibers orientation has large effect on the structural strength of fiber-reinforced concrete [7, 8]. Different methods have been used to study the spatial distribution and orientation of fibers in concrete specimens, including digital image analysis [9-11], X-ray analysis [12], AC-Impedance spectroscopy [13]. In current work the digital image analysis was used to investigate orientation of the fibers. The specimen was cut in the vertical plane (Fig. 2) and by measuring the major axes and the angle of the ellipse of fiber cross-section it is possible to estimate three-dimensional orientation of the fiber.

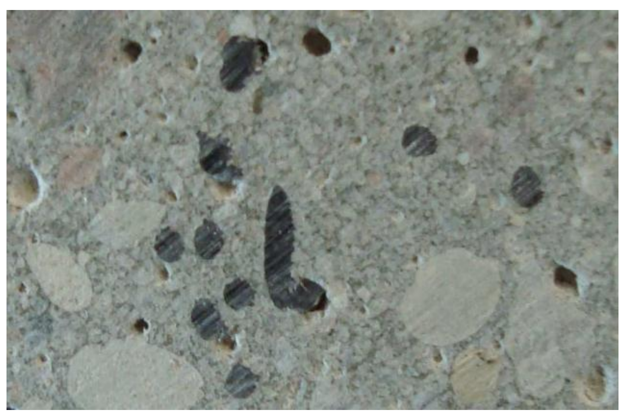
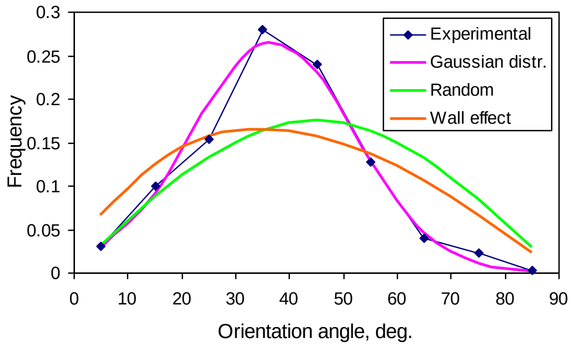
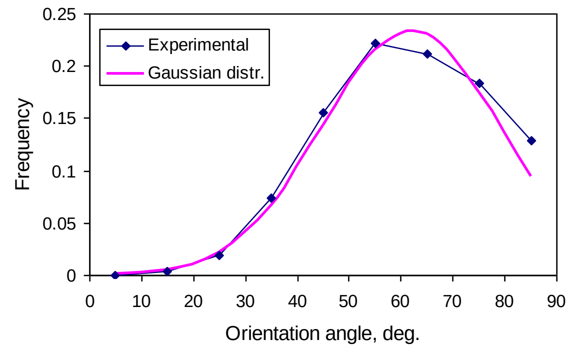


Fig. 2. Micrograph of the specimen's cross-section showing fibers distribution and orientation.

For the analysis of the concrete fracture, it is necessary to know the angle between the fiber and the normal to the fracture plane. Experimental data of the fibers orientation is presented in Fig. 3a with maximum around 35 degrees. Similar results were also obtained in other studies [12, 14]. Assuming random three-dimensional distribution of the fibers, the maximal frequency should be of the fibers with inclination 45 degrees (Fig. 3a). However, the actual distribution of the fibers is never truly random. One reason for this is the wall effect – the fibers should not cross the specimen's boundary. The influence of the wall effect depends on the specimen's size and length of the fibers. Using computer Monte-Carlo simulation the wall effect could be taken into account by requesting that all fibers are placed inside the specimen's boundaries. If one end of the fiber is located outside of the specimen, new random orientation is generated for such fiber, keeping the position of the fiber's center of gravity the same. Due to wall effect, the fibers near the boundaries tend to be aligned more perpendicular to the fracture plane. However, as it is seen in Fig. 3a, the wall effect alone is not sufficient to explain the experimental distribution of fibers orientation. Previous studies have shown that due to vibration the fibers tend to align in horizontal direction [12]. Fig. 3b presents experimental distribution of the angle between fibers and vertical axis. The results show that there are practically no fibers with angle smaller than 30 degrees, with maximum around 50-60 degrees. Therefore, random generation of the fibers orientation for the computer simulation of concrete fracture may lead to significant error and it is better to use experimentally measured orientation distribution.



a)



b)

Fig. 3. The theoretical and experimental distribution of angles between the fibers and normal to the fracture plane (a); experimental distribution of angles between the fibers and vertical axis (b).

Numerical model. Finite element analysis is used to simulate crack propagation in fiber reinforced concrete taking into account random distribution of the fibers. The concrete matrix failure is modeled using approach developed in [15] - cohesive elements are embedded between all solid elements, therefore no predefined crack path is needed. In current work the procedure similar to described in [16-18] is used. The commercial finite element code ABAQUS is used for the generation of the original mesh and solution, and in-house program RiCoh3D [19] was developed to modify the original mesh and embed cohesive elements between all solid elements as shown in Fig. 4. Individual steel fibers are modeled using non-linear springs, connecting the nodes of the adjacent solid elements that cross the fiber. The properties of the spring elements are defined using experimental data from pull-out tests, taking into account the orientation of the fibers according to crack opening direction.

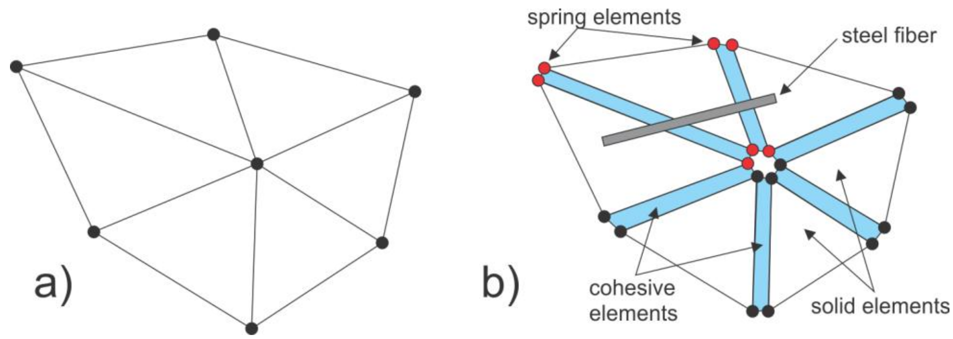


Fig.4. Original finite element mesh (a) and modified mesh with separated solid elements, embedded cohesive elements and spring elements (b).

Fig. 5 shows the example of original 3D solid mesh generated by ABAQUS (Fig. 5a) and cohesive elements embedded between all solid elements (Fig. 5b). The solution algorithm is as follows:

a) generation of the initial mesh of the concrete specimen in ABAQUS software;
b) output of the created model into text file (in INP file format);
c) reading of the INP file and modification of the initial mesh:
    a. every common node between two or more solid elements is duplicated (separate node in the same position is created for each element);
    b. the elements definition is changed by using these duplicated nodes, so that each element becomes separated and not connected with neighboring elements;
    c. the cohesive elements (with zero thickness) are inserted between faces of the neighboring elements, joining them together;
    d. generation of random positions and orientations of steel fibers; identification of all faces crossing fibers; connecting the nodes of solid elements with the same face by non-linear springs;
d) generation of new file in INP format, containing all new elements;
e) reading new INP file into ABAQUS for solution.

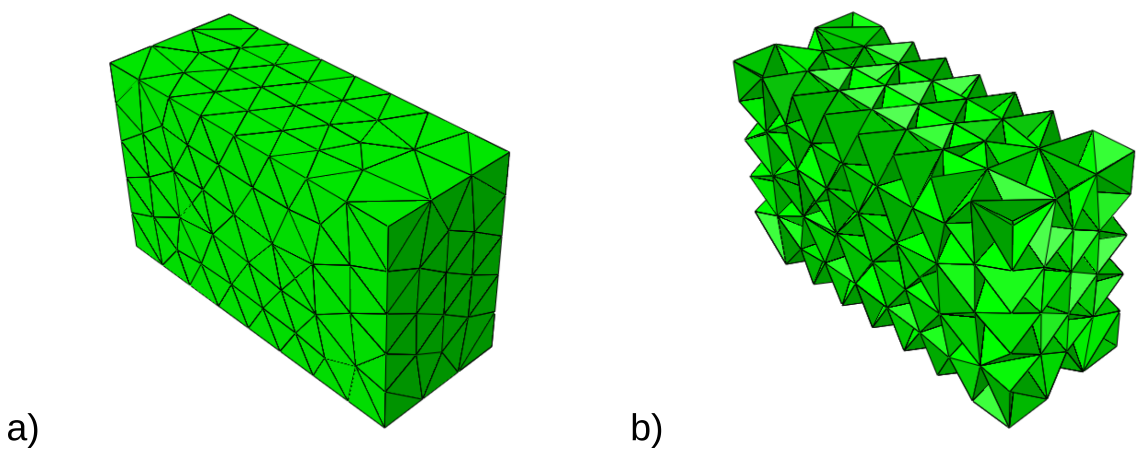


Fig.5. Original 3D finite element mesh (a) and cohesive elements embedded between all solid elements (b).

Results and discussion. As an example the wedge splitting test [20] will be simulated using proposed approach. The specimen's size is 20×20×30 cm with initial crack depth equal 15 cm and side grooves (3 cm deep). The concrete properties were used the same as in [18]: Young's modulus E=28.3 GPa, Poisson's ratio ν=0.2 and mass density $\rho=2.5\times10^3$ kg/m^3. Bilinear softening curve was used for to model the traction-separation law of cohesive elements with fracture energy G_{Ic}=490 J/m^2. ABAQUS/Explicit with the simulation time equal 0.2 s was used to model the crack growth in wedge splitting test. A typical fracture surface for the plain concrete is shown in Fig. 6.

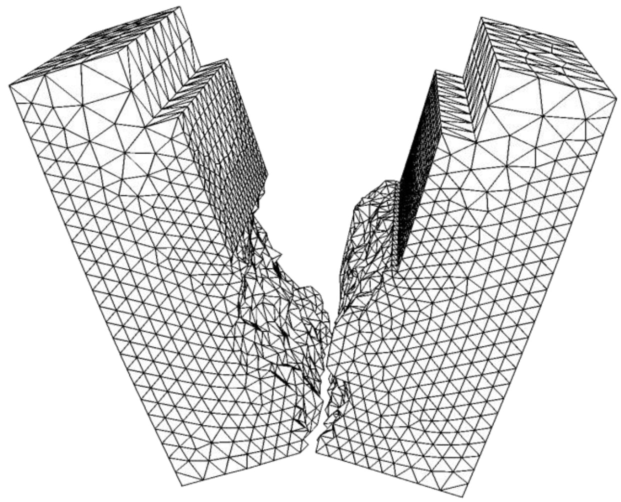


Fig.6. Finite element simulation of wedge splitting test.

Fig. 7 shows the results of finite element simulation of wedge splitting test of fiber-reinforced concrete with different fiber volume fractions. The curves of the same color represent simulations with the same background solid mesh, but different random distributions of fibers. The results show, that small content of fibers (0.25-0.5%) practically does not change the peak load and initial post-peak behavior of concrete sample. The fibers start to work and load increases only at relatively large crack mouth opening. For fiber volume content 1.0% and higher the peak load slightly increases and post-peak curve shows significant load increase compared to plain concrete sample.

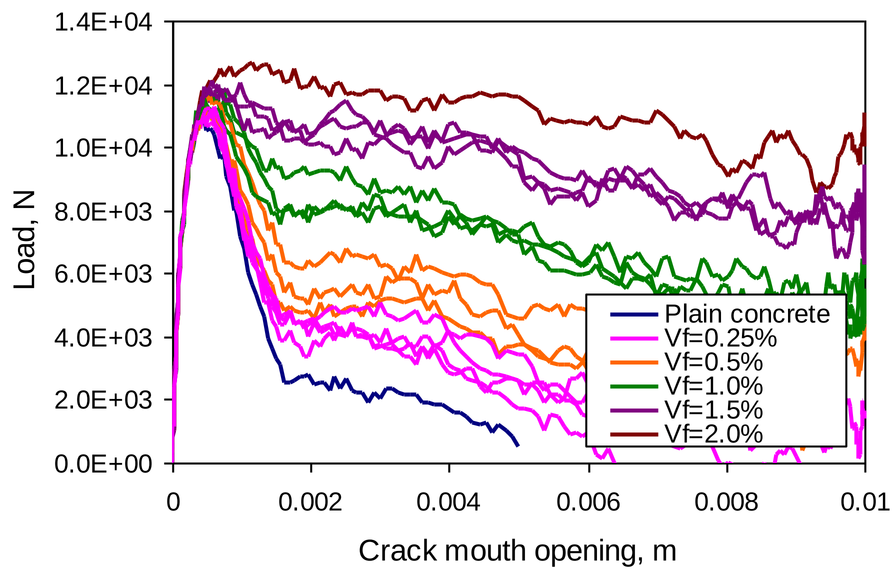


Fig.7. Results of wedge splitting test simulation: load-deflection curves for plain concrete and fiber-reinforced concrete with different fiber volume fractions.

Summary

A two-scale finite element model for the simulation of the fiber-reinforced concrete fracture has been developed. The model indirectly includes distribution of discrete fibers. The bridging action of the fibers is mapped to the nodes of the background mesh as reaction forces, whereas cracking of the concrete matrix is modeled using cohesive zone approach. The model can be used to investigate the influence of different fiber distributions, specimen and fiber geometrical parameters on overall mechanical behavior of fiber-reinforced concrete.

Acknowledgements
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