MICROMECHANICS OF ELASTO-PLASTIC FIBER PULL OUT OF ELASTIC MATRIX

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ABSTRACT

It has been proven by many researchers that the overall behavior of concrete can be improved by the addition of fibers. In the present investigation numerical (FEM) modeling of elastically plastic single straight fiber pull out of elastic matrix volume was realized. Comparison was done with steel fiber is pulling out of concrete matrix. Fiber pulling out micromechanics is governing the macro-crack opening process - fiberconcrete post cracking load bearing capacity is dependent on each single fiber pull out force. Numerical modeling was performed using 3D approach, which takes into account the non-linearity is presenting in physical model in combination with a finite element method (FEM). Straight shape fiber pulling out of concrete block in fiber direction was investigated earlier (Li et al., 1998; Mobasher et at., 1995). In our investigation numerical modeling was performed for straight shape fiber was embedded into elastic matrix under variable angle to applied pulling force and at variable depth.

Key words: pullout, fiber, concrete, micromechanics

INTRODUCTION

Pull out process is the process of pulling a single fiber from concrete matrix. Knowing the force that must be applied for a single fiber to pull it out, we can predict the strength of the structure that is made of fiber reinforced concrete. In fiber concrete fibers which are bridging each particular crack are arranged irregularly and have different angles to the crack plane and depth of each fiber ends embedment into concrete is also variable.

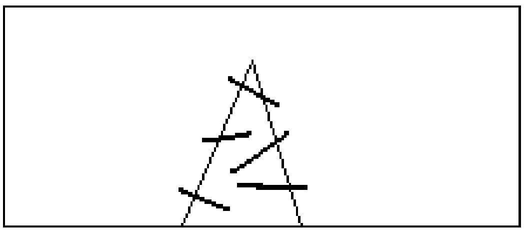

Figure 1. Fibers are bridging the particular crack in fiber concrete. Their location and orientation

In presenting work experiments were made as well as were used earlier obtained results (Krasnikovs A et.al., 2009, 2010), with the goal to clarify what is happening with a single fiber, which is located in the concrete matrix having variable angle and different embedment length in the concrete and is pulling out by external load. Simultaneously the pullout process was modeled, using computer technology. The aim was in comparison of experimental and theoretical data to clarify micromechanical picture of single fiber pull out process and particular this process components – friction, fiber plastic deformation.

MATERIALS

Fibers

Maximum efficiency of fiber-reinforced concrete (reinforced by steel fibers), is possible to achieve with proper component selection and combination of their micromechanical properties. In the case of fiberconcrete ingredients having affordable relative cost, suitable kind of fibers are steel fibers, and their elasticity modulus is 5-6 times higher than the elasticity modulus of concrete. With a certain amount of fibers in the concrete, there is possible to achieve the best strength of the fiber-reinforced concrete, and that will make the greatest contribution to the fiber and concrete mutual withstand to external loads, before and after the formation of cracks in the concrete.

Steel fiber importance in concrete

Differently oriented fibers in concrete can prevent spread of micro-cracks in it. The effect of the fibers depends on their amount and size. Micro-cracking begins at the hydration process stage in cement, so the deformation can be reduced by forming the solid skeleton of the filler particles. Fibers bridging micro-cracks can reduce and delay their growth, despite before cracking fibers are not loaded in concrete. Important is the ratio of the length and

diameter of fiber. Fiber is starting to work when the crack is starting to growth in length and width. Steel fibers are obtained at the market can be divided into two groups: a) fibers that are pulling out of concrete without rupture; b) fibers that are not possible to pull out of concrete without their rupture. First type of fibers- straight, undulated, with different form hooks on the ends etc., second type – fibers with cones or balls on the ends, etc. Straight fibers belong to first group of above mentioned fibers. Commercial fibers are designed in such way that each fiber start to slide in the concrete before it will reach the limit of elasticity. If the fiber is broken, in the concrete, it cannot continue to carry the tensile load. If the fiber in concrete remains intact, it works together with a concrete and is able to constrain even wide cracks.
Fiber load bearing properties are highly dependent on the fiber's steel strength, shape, surface geometry, strength of concrete, as well as adhesion to concrete (specially for coated fibers).

Pull out experiments

Fibers pullout micro mechanism is governing structural elements mechanical behavior under applied external loads. With the goal to more closely examine this phenomenon, experiments with single fiber pull out of the concrete matrix were executed.

Pull out specimen elaboration

Moulds of wooden plywood, consisting out of two separated similar parts, were manufactured. Each formwork internal sides were covered by plastic tape, to prevent the matured sample from sticking to the mould. Between the form's parts was placed a plastic film (separator). Single fiber was embedded into both sample parts going throw the separator at its middle part. This film is separating concrete parts of the sample from each other and is simulating the crack. This ensures that only fiber is bearing the external stretching load in the process of tearing the sample. The fiber is placing at a certain angle to direction of the stretching force and at a certain depth by pulling out end. Embedment was: 5, 10, 15, 20 and 25mm, and the fiber inclination angle to the stretching force direction: 0 °, 10 °, 20°, 30°, 45°, 60°.Samples were matured at least 28 days. Then with the Zwick / Roell Z150 computer governing mechanical loading machine with additional 1kN dynamometer, experiments on the fiber pulling-out were conducted. Concrete sample both parts mutual displacement was fixed by video extensometer "Messphysik". As results of the Pull out experiment F-δ (force-displacement) curves for fibers with different inclinations and different embedment in concrete were obtained. Concrete compressive strength was 70Mpa. Steel fibers had strength equal to 1050Mpa.

Simultaneously, numerical simulation of the elasto-plastic fiber pull out process was executed using finite element method (FEM).

MODELING AND RESULTS

Creating a pull out model using FEM is necessary to consider parameters that determine the outcome of modeling. In our investigation friction between concrete matrix and steel fiber surfaces is taking into account using finite contact elements. If we are observing two rigid bodies are sliding one corresponding to other and between them is appearing dry, called Coulomb, friction force (see Fig.2) the coefficient of friction between them is 0.45 if one body material is steel and other is concrete. If dry friction is realizing between two bodies, the value of friction force is dependent on friction coefficient and force is compressing bodies. In the case when steel fiber is in a concrete, as compressing force is acting concrete matrix shrinkage.

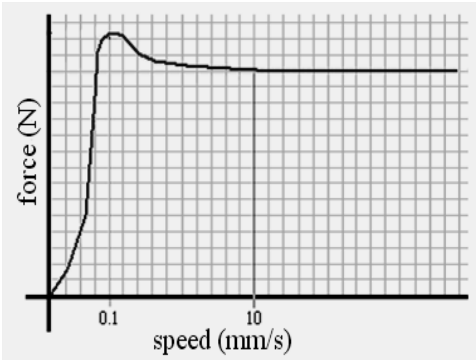

Figure 2. Coulomb friction curve

The reason of concrete shrinkage is removal of excess waterwhen it dries. In order to obtain the value of shrinkage, an experimental investigation was conducted. Plain concrete specimen with dimensions 300x55x55mm and an extensometer mounted on one of the sample end was exposed 28 days under room external conditions (see Fig.3).During this time the concrete dried and shrinked, and after 28 days was found that the concrete shrinkage is 0,073%.

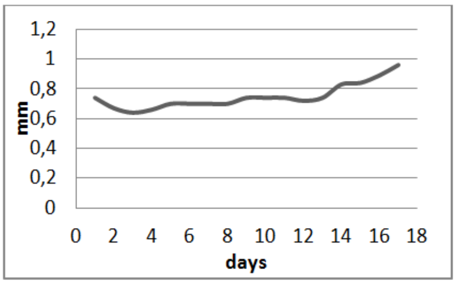

Figure 3. Shrinkage experimental curve

Modeling volume consists of a straight steel fiber with a length 50 mm and a diameter is equal to 0.75 mm that is placed in the concrete matrix (see Fig.4). Volume with a straight fiber is radially symmetric, because that for stress fields calculation only a quarter of the volume was taken for numerical modeling. The fiber was placed into the matrix for different lengths: 5, 10, 15, 20 and 25 mm. Displacement of dead end of the concrete matrix in fiber direction is equal to zero (see Fig.4), on all planar side surfaces symmetry boundary conditions were applied. Fibers outer end was pulled out with constant velocity and between fiber and concrete matrix were placed contact elements with dry Coulomb friction in a form shown at figure 2 between them.

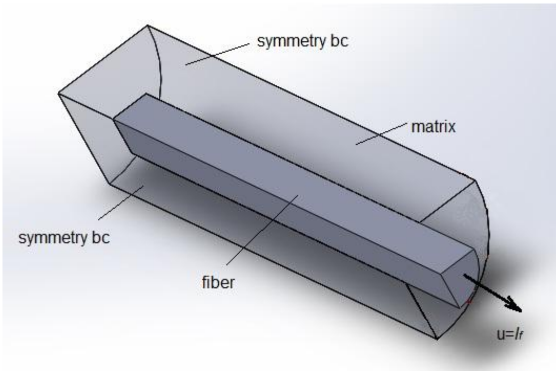

Figure 4.FEM modeling volume geometry and boundary conditions

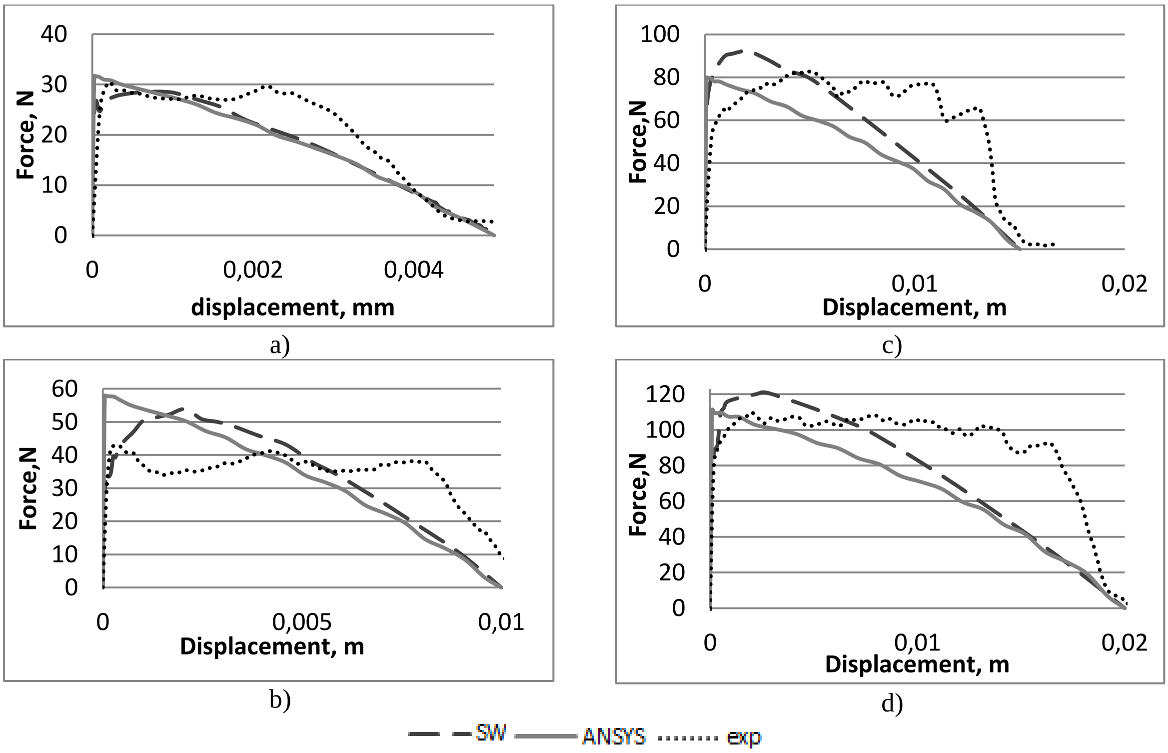

Figure 5a-d. Pull out experimental curvecomparison with numerical modeling data(were obtained using SolidWorks and ANSYS FEM software) for steel fibers were embedded in concrete at different depth: a) 5mm; b) 10mm; c) 15mm; d) 20mm

Young modulus of concrete matrix was: E = 30000 Mpa; Poisson‘s ratio of concrete matrix $\upsilon = 0.2$; Young modulus of steel fiber: E = 200 GPa, Poisson‘s ratio of steel fiber: $\upsilon = 0.32$. Concrete matrix was elastic, fiber was elasto plastic.

In result of numerical simulation, curves "force-displacement" for the straight fibers that were placed in the concrete for 5, 10, 15 and 20 mm Were obtained and were compared with experimentally obtained (see Fig.5). Simulations comparison with experimental data was shown inability to approximate experimental curves at fiber pull stage. Is possible to conclude- fiber movement in the channel in concrete matrix is not happen as movement under dry friction movement conditions with constant friction coefficient.

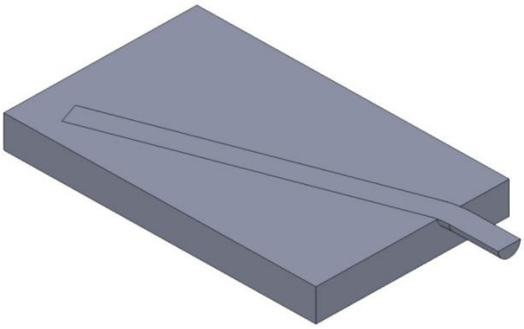

Figure 6. Pull out model for fiber is embedded under the angle to pulling out force direction

Only if friction coefficient is non-linearly changing during motion successful approximation can be done. Was supposed, that during fiber sliding small concrete matrix particles (small grains of sand or cement stone) are separated from concrete matrix channel internal surface and rolling between concrete and steel surfaces are making plugs. Such pug existence leads to increase of applied force till the plug is demolish and sliding is continuing till future plug formation (peaks on experimental curves in figure 5).

Similar model was created in a case when fiber had different declination angle to pulling out force direction and different embedment depth (see Fig.6). In this case two micromechanical mechanisms – friction and plasticity of the fiber are working simultaneously. Curves "force-displacement" numerically obtained in the simulations by finite element method were compared with the curves obtained experimentally and are shown in Fig.7.a-d for fibers inclined under different angles to load direction and in Fig.8.a-d for fibers embedded at different depth.

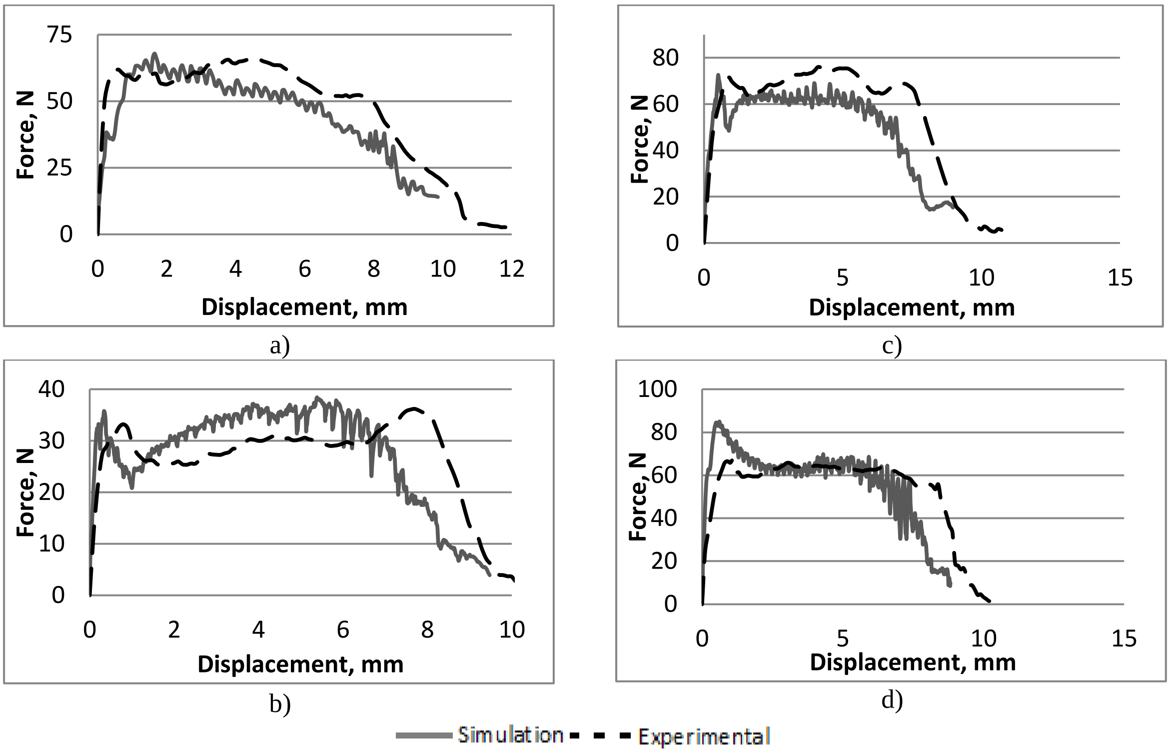

Figure 7. Experimental and modeling curves for fibers were embedded into the matrix on a depth 10mm: a) fiber is oriented under the angle 20° to the applied force direction; b) fiber is oriented under the angle 30° to applied force direction; c) fiber is oriented under the angle 45° to applied force direction; d) fiber is oriented under the angle 60° to applied force direction

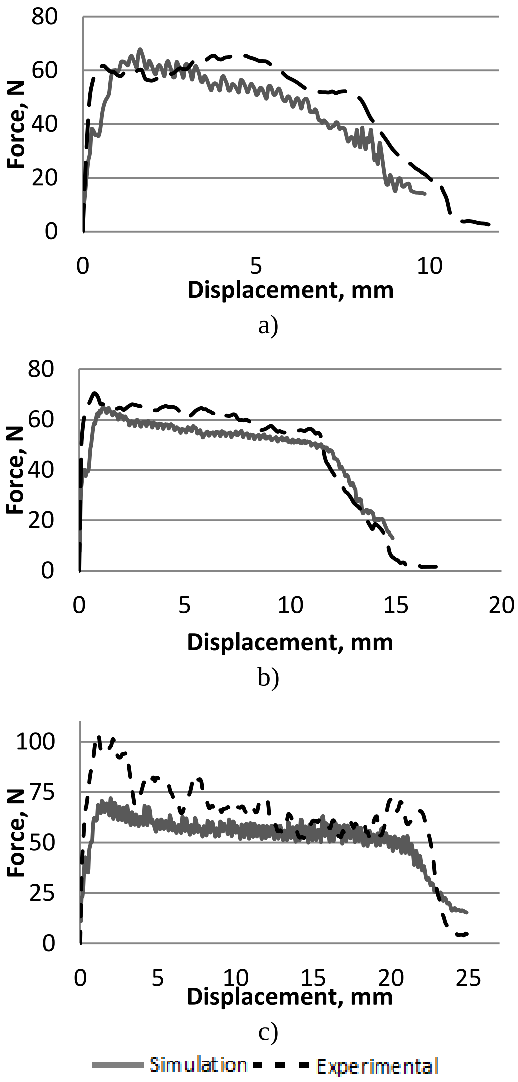

Figure 8. Experimental and modeling curves for fibers were oriented under the angle 20° to applied force direction: a) fiber is embedded into the matrix on a depth 10 mm; b) Fiber is embedded into the matrix on a depth 15 mm; c) Fiber is embedded into the matrix on a depth 25 mm

CONCLUSIONS

Detailed 3D numerical (FEM) investigation for elasto-plastic single fiber pull-out of concrete matrix was realized. Comparing pull out theoretical data for fibers which were embedded orthogonally to concrete block with experimental results, was shown, that model based on assumptions about dry 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 cause fiber friction and plugs formation around the fiber can be mentioned as possible this situation explanation. 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 plug. Experimental and numerical data coincidence increase for fibers which are pulling out under an angle. Plastical fiber behavior incorporation into solution compensates uncertainty in nonlinear friction simulation.

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