FRACTURE AND POST-CRACKING BEHAVIOR PREDICTION FOR GLASS AND CARBON FIBRE REINFORCED CONCRETE CONSTRUCTION MEMBERS

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Abstract

Experimental investigation of AR glass fiber and carbon fiber concrete strength and post cracking non-linear behaviour were realized. Simultaneously fiber pull-out micromechanical investigation was realized experimentally (for glass and carbon single fiber and fiber bundles) and numerically (using FEC ANSYS). Structural fiberconcrete fracture model were elaborated. On the base of micromechanical results predictions for fiberconcrete non-linear post-cracking behaviour were successfully made for fiberconcrete prisms subjected to 4-point bending. Model predictions were experimentally verified.

Keywords: Carbon and AR glass fibres; concrete; micromechanics.

1 Introduction

Plain concrete has brittle nature of results in its poor resistance to crack propagation. Inclusion the short dispersed fibres in concrete help to prevent a catastrophic type of failure by transferring the stresses across the cracked matrix. Fibres are bridging each crack resulting to quasi-plastic material post cracking behaviour. If we want to predict fiber concrete material cracking and post-cracking behavior, and the same time are looking for tensile strength increase and quasi-plastic (with few % deformation without loosing load bearing capability) material post-cracking behavior, the study of single fiber and fiber bundle pull-out mechanisms out of cement matrix is important. An overview of fiber/matrix interfaces micro-mechanical investigations is given by Bentur [1] and Victor C. Li [2]. Additional information can be found in an article of Bentur [3]. Gray and Johnston [4] observed single fiber pull-out testing techniques for interface property characterization. Fracture experimental investigation for glass and carbon short fiber concretes [5] recognized main micro-mechanisms of fiber bridging cracks in material. In present paper, investigation of single and few non-metallic fibres micro-mechanics embedded into concrete matrix under external loads were performed numerically (using FEM approach) and experimentally. Micromechanical data were used for fiberconcrete cracking and post-cracking behaviour based on elaborated structural model. Prediction results were validated by 4-point fiberconcrete bending tests data.

2 Micro-mechanics

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2.1 Single fiber pull-out numerical simulation

Single fiber is oriented orthogonal to concrete surface and is pulling out. Such situation is simulating the fiber is bridging the crack closely orthogonal to flanks surfaces. At the same moment this is the case of experimental pull-out test were performed by different authors investigating fiber/matrix interfaces in cement based composites [2,4,5]. External load is applied to fiber, pulling it out of concrete matrix. Our and another authors experimental observations shown four main stages of such procedure:

a) fiber and concrete matrix are bonded together (perfect bond), all deformations in system are elastic; b) cylindrical delamination crack is starting from the outer concrete block surface propagate into material between fibre and concrete matrix. Crack is growing mainly by mode 2; c) when fiber embedment is small (short fiber or pulling out the shorter end of fiber which is bridging the crack) delamination is reaching all length of fiber after that fiber with friction is pulling out. If fiber embedment is large, fibre is breaking at the length L in concrete, after what free fiber end with friction is pulling out of matrix; d) stretched fiber breaks out of concrete.

Fibers breaking in material according scenario a-c are responsible to fiberconcrete post-cracking quasi-plastic behaviour and are the subject of present investigation. Simulations have been done by ANSYS structural program with mechanical properties of materials: concrete matrix: E = 30000 MPa, υ = 0.2; AR Glass fiber: E = 70000 MPa, υ = 0.2; Carbon fiber: E = 300000 MPa, υ = 0.2; Interlayer: E = 500-3000 MPa, υ = 0.25.

Three numerical 2D models were under investigation. **First**: single glass (carbon) fiber is embedded into concrete matrix with perfect bond between them and subjected to external pulling load. Maximal tensile stress in stretched fiber is concentrated in crossection coinciding with concrete outer surface (see Fig.1 (left picture)). Similar situation is with shear stress on the interface between matrix and fiber (see Fig.1 (right picture)). Horizontal coordinate x=35∗7E-03mm corresponds to concrete surface. R (R=7E-03mm) is the fiber radius. **Second model** is describing the situation, when between

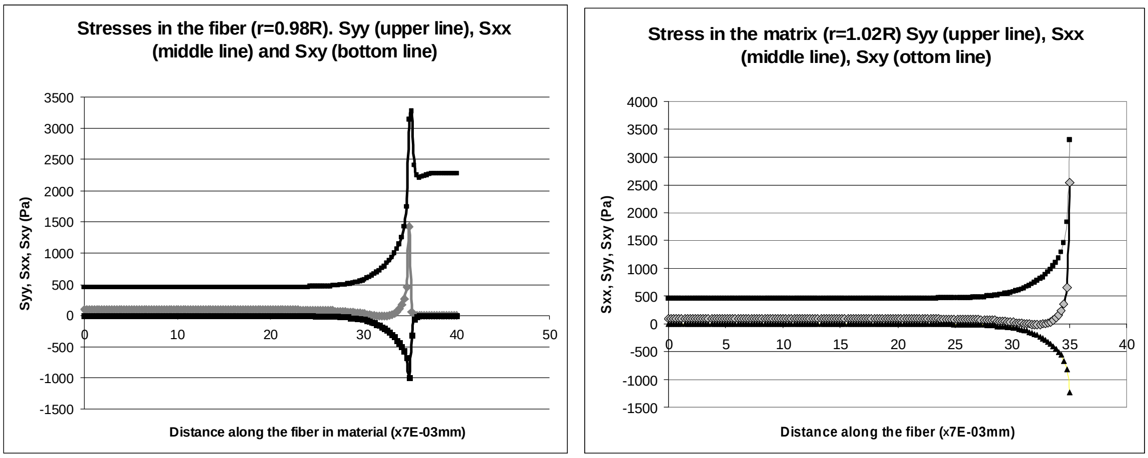

Fig. 1 Stresses in the fiber in vicinity of fiber/matrix interface (r=0.98R)(left picture)). Stresses in the matrix in vicinity of fiber/matrix interface (r=1.02R)(right Picture). Between fiber and matrix is perfect bond. Syy-upper line; Sxx-middle line; Sxy-bottom line.

pulling out fiber and matrix is growing delamination. In delaminated area fiber and matrix are debonded. Each mutual motion in this zone performs with friction. Numerically this situation was simulated incorporating soft interlayer between fiber and matrix. Stresses in fiber along the line parallel to fiber axis in vicinity to interface with matrix (0.98 of fiber radius) are shown at Fig.2 (left picture) and in the matrix (r=1.02R) at Fig.2 (right picture). Peaks on the lines (going from left to right) corresponds to: a) fiber end in concrete (small peaks); b) beginning of delamination zone (middle peaks) (x=25*7E-03mm); c) outer surface of concrete block (x=35*7E-03mm) (right peaks). Stress peaks at the front of delamination zone (corresponds to singularities in classical solution) are explaining mechanism of fibre break at some distance in concrete volume, because during delamination growth elevated overstress is crossing different fiber crossections in concrete till the weakest is reached. Simultaneously overstress is decreasing with the distance from the crack (outer surface of concrete block) surface and increasing with fiber/matrix interface friction increase (corresponds to concrete matrix with higher compressive strength). At the same moment overloads in the matrix are rising into concrete body micro-cracks formation around the fiber. These cracks were observed experimentally. **Third numerical model** were elaborated to describe fiber end sliding motion after the break in

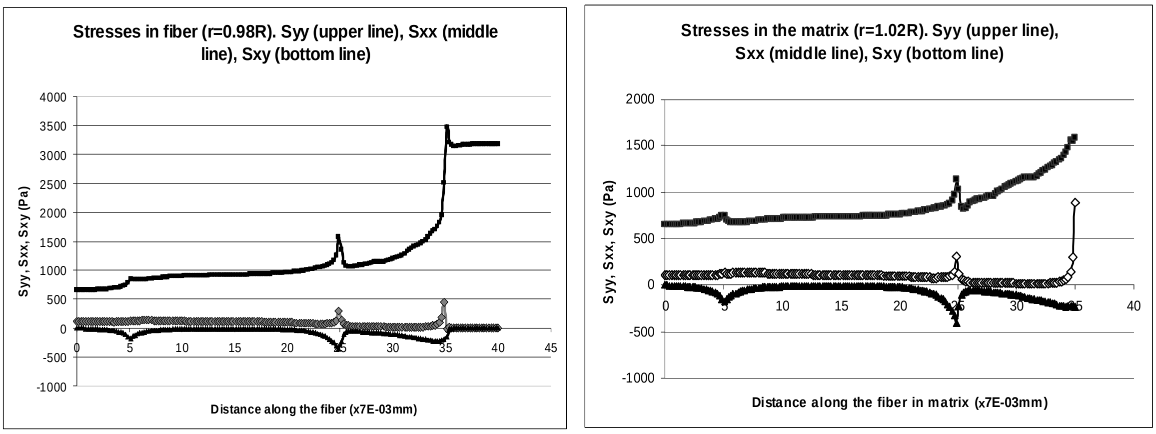

Fig. 2 Fiber is partially debonded in concrete. Stresses in the fiber on the line parallel to fiber direction (r=0.98R) (left picture). Stresses in the matrix on the line parallel to fiber direction (r=1.02R) (right picture). Stress in y direction along the fiber S_{yy} (upper line), stress in x direction –direction orthogonal to fiber direction S_{xx} (middle line) and shear stress S_{xy} (bottom line).

the concrete matrix or in the case when delamination reach the embedded end of fiber. FEM model with contact elements between fiber and matrix were exploited.

2.2 Fiber bundle pull-out numerical simulation

Three above mentioned models were realized for fiber bundle with 2, 3, 12 and 800 fiber in a bundle. Traditionally non-metallic (glass, carbon) short fibers, are ready for concrete mix, are available in a form of fiber bundles (chopped strands) with 600 to 1200 filaments in each bundle. During fiberconcrete mixing cement paste are penetrating into bundles only partially, forming external shell (composite fibers in cement paste) and the core (fibers without paste between them). Such bundle bridging the macro-crack is failing by rupture of fibers in composite shell and consequent core sliding out (this process governs by friction fiber to fiber) and easily can be recognized on Fig.3. Looking on stress profiles becomes clear load bearing mechanism for such bundles. Bridging the crack main load is bearing by bundle shell, internal core starts sliding motion when shell fibers rupture in crack's flanks and are pulling out according to above mentioned second and third models.

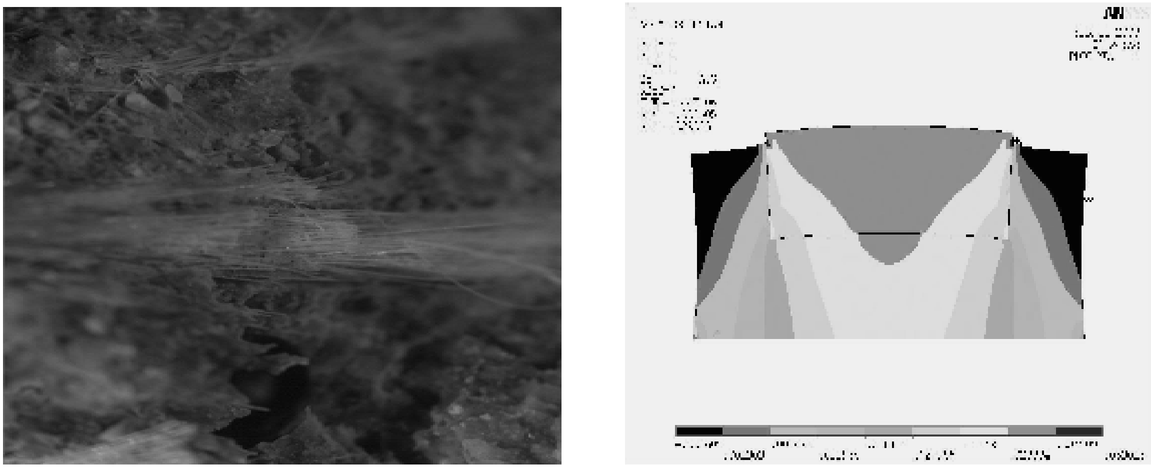

Fig. 3 Fiberconcrete rupture surface with glass fiber bundle on it. Bundle has external composite shell (fibers with cement paste between them) and internal core (fibers without cement paste) (left picture). Stresses in the concrete and in the fibers in a case of 800 filaments in the bundle. Fibers have perfect bond between outer fibers and concrete and week bond between fibers in the bundle core. Stress in y direction S_{yy} (right picture).

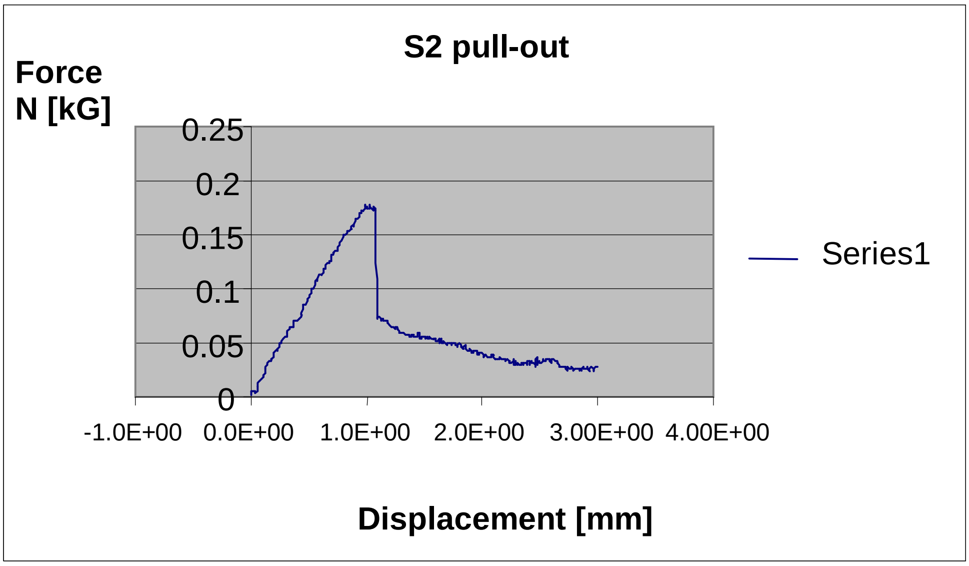

Fig. 4 Single glass fiber pull-out experimental load-displacement curve.

2.3 Single fiber and fibre bundle pulling out experimental validation

Obtained numerical results were validated by performed experimental tests for single (see Fig.4), two and 600 fibers (bundle). Main fiber and matrix failure mechanisms were recognized. Single glass and carbon fibers were embedded into concrete matrix on the depth 10mm and 20mm, pulling out such fibers for one part of samples fibers fail out of concrete. Fibers, in other samples, fail in concrete and after that were pulled out. Pulled out part of each fiber haven't exceeded 1.5mm. This mechanism directly corresponds to models b,c. For bundles having 600 filaments, fibers in outer shell fails according mechanisms b,c. Bundle central core were pulled out and had full length (this effect depends on how many concrete paste penetrated bundle embedded end).

3 Macro-mechanics

Fiberconcrete prismatic samples with the size 10x10x40cm were elaborated. With the goal to control the location of macro-crack formation place, samples were cutted by dimant saw at the middle of the bottom surface of the prism (at the depth of 1 cm, thickness of the saw was 2mm) and were tested under 4 point bending conditions (distances between supports were: 30cm between bottom and 10cm between upper). 5cm were the distance from the each edge to the nearest bottom support. Fully computer driven testing mashine Zwick -150 (with ultimate force 150kN) were used. Stress- prism midpoint deflection diagrams

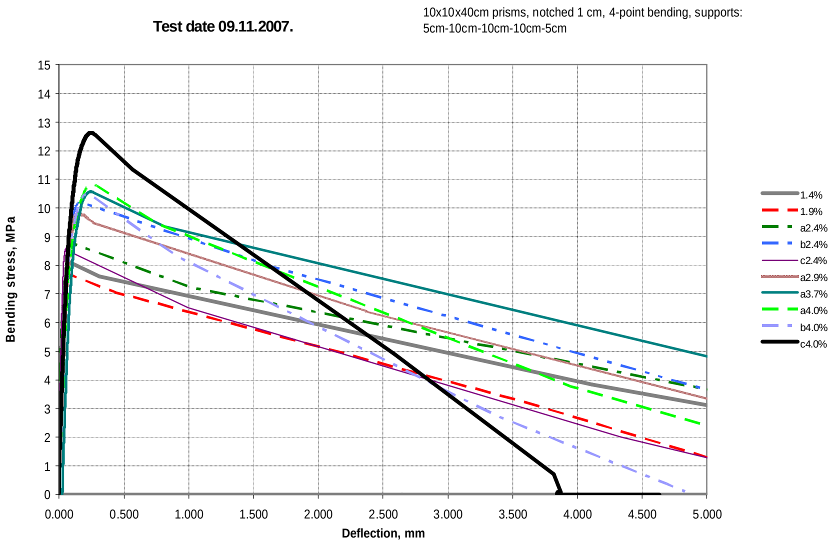

Fig. 5 Stress-midpoint deflection diagrams for glass fiberconcrete (subjected to 4-point loading) with fiber content V_f from 1.4% to 4%, and fiber strand length equal to 12mm.

for glass fiber and carbon fiber concrete were obtained. Plots in Figure 5 corresponds to short 12 mm AR-glass fiber strands fiberconcrete tensile strength evaluation. In all cases concrete matrix with the same compressive strength were used. In all cases all curves have approximately the same initial elastic behaviour region (linear part on each curve at loading beginning). From the peak value, intensive fibers and strands pulling-out from the matrix is lanched simultaneously with partial fiber breakage in the most loaded strands, bridging the main macrocrack. Consequently, fibers amount increase in concrete leads to increase of the maximal bearing stress (peak value on the curve). The fibers amount started with 1.4 % at the beginning leads to bending stress peak value equal to 8 MPa and correspondingly last ratio was used 4.0 % which gave peak value higher than 12 MPa. For high fibers volume fraction values we have the saturation (in our case V_f =4%). This saturation can be explaned by lower rate of concrete paste penetration into bundles, for high values of V_f (in this case fresh fiberconcrete is very stiff and unworkable). In this case, each bundle pull-out force is decreasing. Post cracking behaviour (curve part after the peak value) is quit different for fiberconcretes with short (12 mm glass fibers at Fig.5) and long (40 mm long carbon) fibers (were we can found quasi-plastic behavior).

Experimentally obtained pull-out laws were used as the main input data for the proposed structural FRC fracture model [6] and non-linear behavior of FRC beams under bending loads were predicted. Predictions were compared with experimental test data for prismatic samples (with the size 10x10x40cm) 4 point bending.

4 Conclusions

Numerical investigation for non-metallic (glass, carbon) single fiber and fiber bundles pull out of concrete matrix micromechanics (detailed micro-stresses and micro forces) were performed. Simulations results were compared with performed pull out experiments. Main fiber and bundle load bearing and rupture mechanisms were recognized. On the base of experimentally obtained pull-out data fiberconcrete fracture and post-cracking behaviour prediction for prisms under 4-point bending loading conditions were done. Prediction results were compared with experimental data.

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