PULL-OUT MICRO-MECHANISM FOR FIBERS IN CONCRETE

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Abstract: *Applied load is inciting numerous cracks formation in fiber reinforced concrete (FRC) structural member. Fibers are bridging the crack. Fiber pulling out micromechanics is governing the macro-crack opening process. Post cracking load -bearing capacity is dependent on the each single fiber as well as fibers bundle pull-out process. In the present paper are presented numerical simulations and experimental investigations results of a single and few non-metallic fibers were embedded into concrete matrix and were subjected to external applied pulling load. Numerical modeling was performed using 3D FEM approach. Experimental data analysis shown that the pull-out process for single fiber can be divided into three stages- a) fiber pull-out with perfect bond between fiber and concrete matrix; b) fiber pull-out with partial debond (cylindrical crack) between concrete matrix and fiber, started from concrete matrix surface; c) fully debonded fiber pull-out of concrete matrix. All above mentioned stages were investigated theoretically and experimentally. Few fibers bundle has "telescopical" pull-out mechanism if it is not penetrated by concrete properly.*

1 INTRODUCTION

Plain concrete is brittle, addition a short randomly distributed fibers leads to quasi-plastic

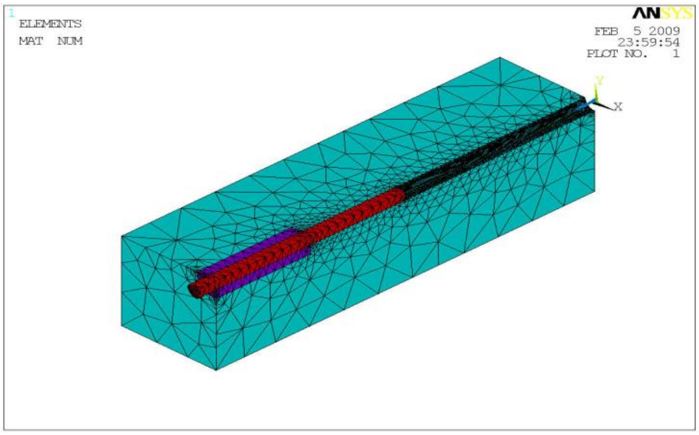
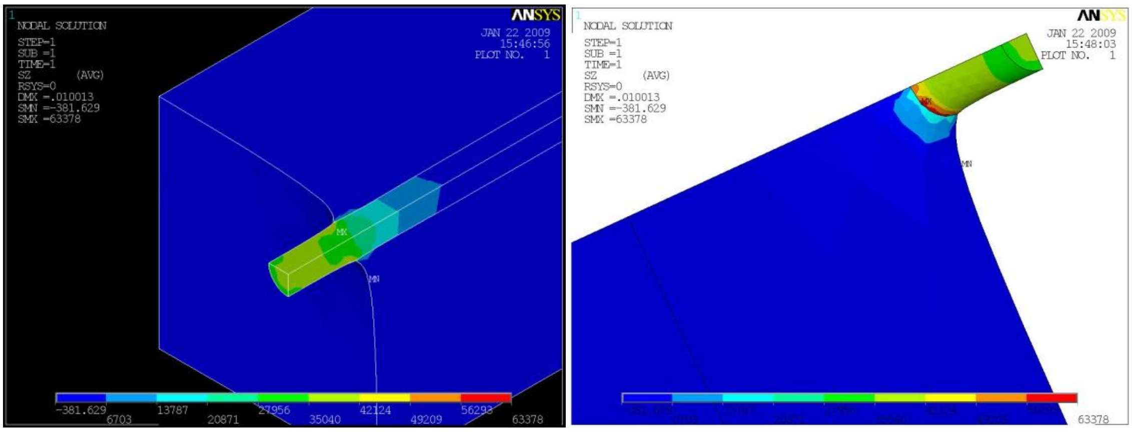


Figure 1. 3D finite element model of single glass fiber embedded into the concrete matrix. Fiber is pulling out by external load. Fiber is partially debonded (is modeling by "soft" interlayer between fiber and matrix started from concrete surface).

material post cracking behavior. Fibers are mainly pulling out, during the fiber concrete multiple cracking, that's why the study of fiber pull-out micromechanics is important [1]. An overview of such type research works as well as results of performed 2D numerical investigations were published in [2]. Additional results can be found in the articles [3-7]. Fracture microscopical investigation for glass and carbon short fiber concretes [2] recognized main micro-mechanisms of fiber bridging cracks in material: a) dispersed single fibers are bridging cracks; b) fibers bundles (of different size) are bridging cracks. In the present paper, investigations of single and few non-metallic fibers micro-mechanics embedded into concrete matrix under external loads were performed numerically using 3D FEM approach and experimentally.

2 SINGLE FIBER PULL-OUT MICROMECHANICS

Corresponding to investigation performed in [2], single fiber pull-out process can be divided into three stages- a) fiber pull-out with perfect bond between fiber and concrete matrix; b) fiber pull-out with partial debond (cylindrical crack) between concrete matrix and fiber, started from concrete matrix surface; c) fully debonded fiber pull-out of concrete matrix. 3D FEM model was used in calculations. Material properties were: concrete matrix: E = 30000 Mpa, υ = 0.2; glass fiber: E = 70000 Mpa, υ = 0.2; „soft" material (corresponds to interlayer in fiber/concrete matrix debonded zone (see Fig. 1)): E = 500-3000 Mpa , υ = 0.25 (was accepted that debonded area between fiber and matrix is simulated by thin interlayer with low mechanical properties). Fiber is pulling out of the concrete. Longitudinal stresses (z – direction) in concrete and fiber, in the case of perfect interface bond between fiber and matrix (concrete) are shown in Fig.2 (a-b).



a) b)

Figure 2. (a-b)-An axial stress (in z-direction) around and inside single glass fiber embedded into concrete matrix. 3D situation at the first stage of pull-out test, fiber is perfectly bonded with matrix (concrete).

An axial stress (in z- direction) analysis was shown that the maximum stress in the fiber appear at the concrete block front surface crossection, where the fiber emerges out of the concrete matrix. This is the reason for fiber to rupture at this crossection (such results were obtained in our experiments). If it is not happening we have a pull-out scenario. According to pull-out scenario future pull-out force increase leads to debond appearance and future growth between fiber and concrete matrix. Debonding starts progressively from the interfacial surface of concrete matrix and is growing inside between the fiber and the concrete according to increasing external pull-out force. In modeling was introduced thin "soft interlayer" between matrix and fiber, on the length of cylindrical debond in the material (see Fig.1.). Really it is partially destroyed concrete matrix (concrete stone and sand small pieces). Numerical calculations were shown existence of two dangerous crossections in the fiber: first –at the outer surface of concrete matrix (where fiber is foisting oneself out of concrete) and second

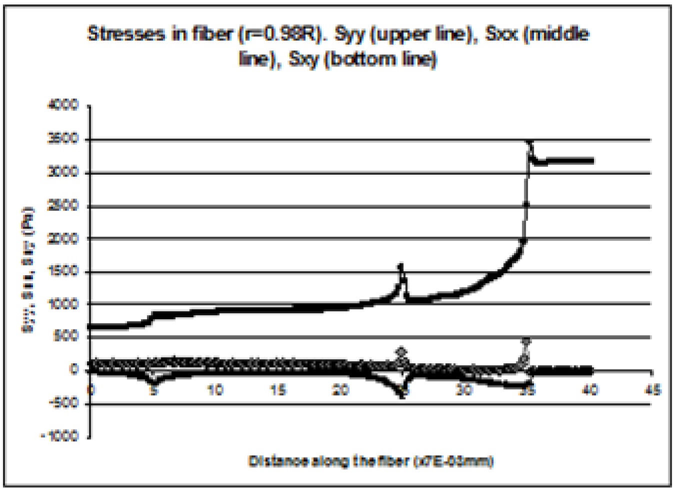


Figure 3.a. Axial stress profile in the fiber (in the case of partially debonded glass fiber in concrete matrix) (2D calculation)).

at the end of debonding zone (see Fig. 3.a-b). Stresses in fiber along the line parallel to fiber axis in vicinity of interface with matrix (0.98 of fiber radius) are shown in Fig. 3.a, 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).

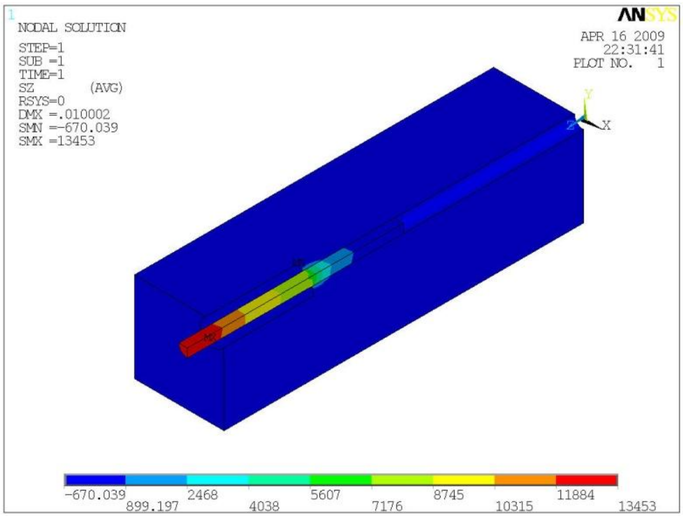


Figure 3.b. Axial (in fiber direction) stress distribution in partially debonded glass fiber and concrete matrix.

At the same time debond (cylindrical crack) is tending to grow corresponding to shear stress peak existing on the tip of debond crack. In the framework of fiber pull-out scenario we have three options: first- fiber breaks at crossection coinciding with concrete block outer surface (this situation is still similar to previously mentioned break without debonding);

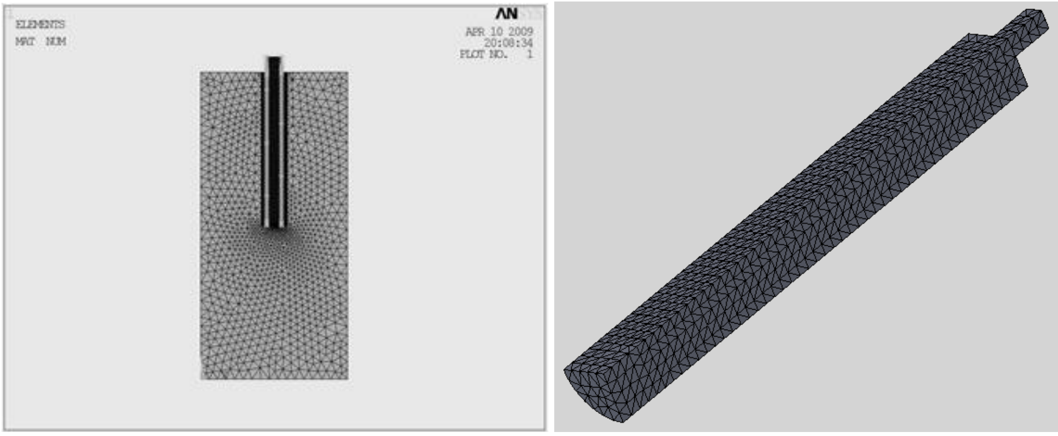


Figure 4. a) 2D fiber sliding motion numerical model; b) 3D model. Between fiber and matrix are contact elements.

second - fiber breaks at the end of debond zone in concrete block; third – debond growth leading to increase of pulled out fiber part length; third- fiber is pulling out (with friction at the interface fiber/concrete matrix). Third possibility is realizing in two cases: fiber breaks at debond zone end (second stress peak at Fig. 3.a.) and fiber end with friction is pulling out of concrete. Debond zone is reaching all embedded fiber part and this part is pulling out of concrete. This possibility was investigated creating FEM model with contact elements between fiber and matrix in debonded zone (see Fig. 4 a-2D model; b-3D model). Single glass fiber is pulling out, all of bonding tights are lost, and then frictional sliding motion will start under the tension load to extract the fiber outside the concrete matrix (see Fig.5.a).

3 EXPERIMENTAL VALIDATION

Obtained numerical results were validated by performed experimental tests for single glass (see Fig.5) and carbon fibers. Single glass (and carbon) fiber was embedded into concrete matrix on the depth 10mm and 20mm. Pulling out such fibers two different scenarios was obtained: for one part of samples fibers fail out of concrete (Fig.6); in other samples, fiber delaminated and fails in concrete and after that were pulled out (Fig.7). Pulled out part of fiber haven't exceeded 1.5mm (fibers part outside the concrete was painted before the test).

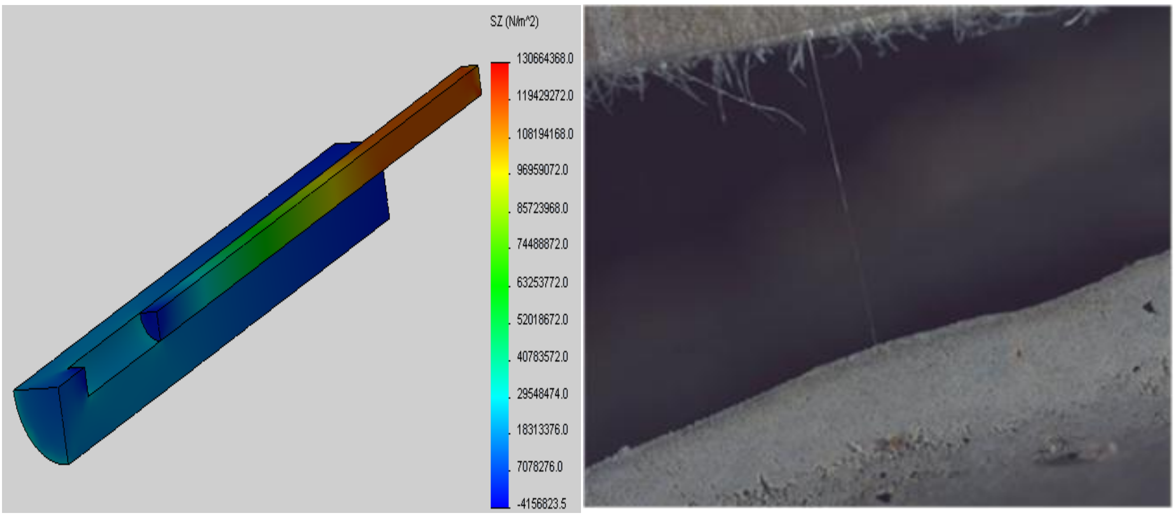


Figure 5. a) Fiber with friction is sliding out of matrix. b) Sample with embedded glass fiber for the single fiber pull-out test.

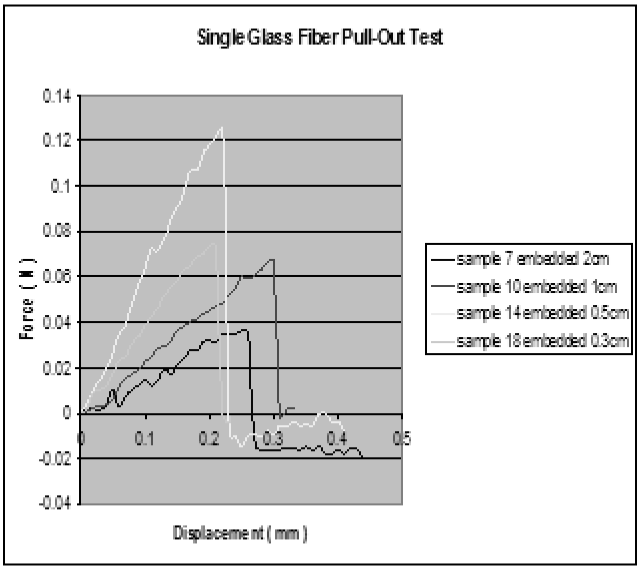


Figure 6. Applied force (pulling out fiber) – displacement curves corresponding to the case of fiber rupture out of concrete matrix (close to concrete surface).

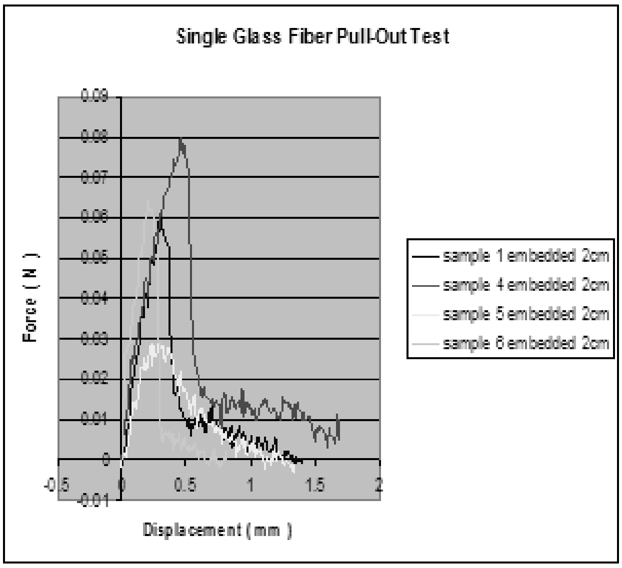


Figure 7. Applied force (pulling out fiber) –displacement curves corresponding to the case of fiber/matrix debonding and fiber rupture inside the concrete block. After what fiber end with friction was pulled out (horizontal part of post peak part of the curves).

Big experimental scatter can be explained by matrix non-homogeneity (sand grains in concrete was up to 2,5mm in diameter, fiber diameter was 12mkm (glass fibers) 9mm (carbon fibers and mechanical fiber-matrix interaction mechanism. Experimental data comparison with numerical simulation allowed to obtain fiber critical length and fiber –matrix friction coefficient values (for tested couples glass fiber concrete and carbon fiber-concrete) during pull-out sliding motion: for glass fibers it was in the range 0.18-0.28, for carbon fibers 0. 12-0.2.

4 FIBERS BUNDLES PULL-OUT

Three above mentioned models: a) perfect bond between fibers and matrix; b) fibers with growing delamination on fiber/matrix interface and c) fibers pull out with friction were realized for fiber bundle with 2, 3, 12 and 800 fiber in bundle. Numerical results are shown in Fig. 8-10. Traditionally non-metallic (glass, carbon) short fibers are ready for concrete mix available in a form of fiber bundles (chopped strands) with 600 to 1200 filaments in each bundle.

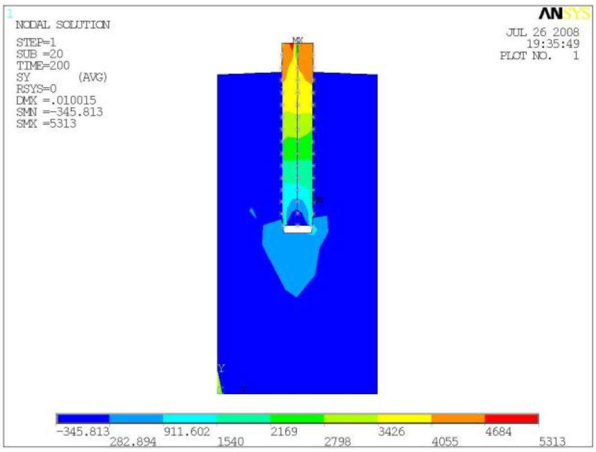


Figure 8. Tensile stress (in fibers direction) in the case of sliding motion of 2 fibers with different friction on the interfaces fiber/matrix and fiber /fiber.

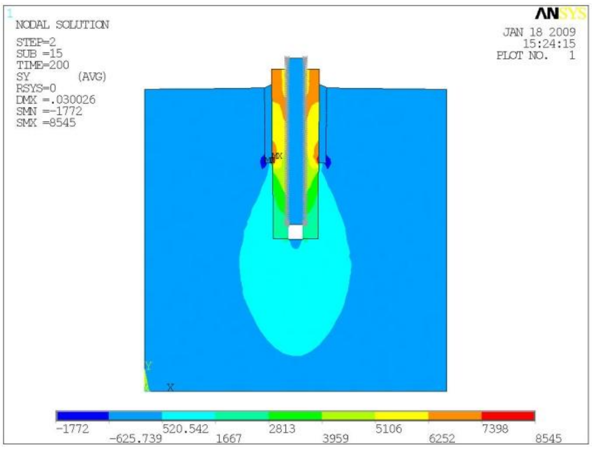


Figure 9. Three fiber pull out. Axial stress in concrete and fibers in the case of delamination and internal fiber sliding motion with friction.

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 in Fig.10 and 11. Looking on stress profiles (Fig.11) 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.

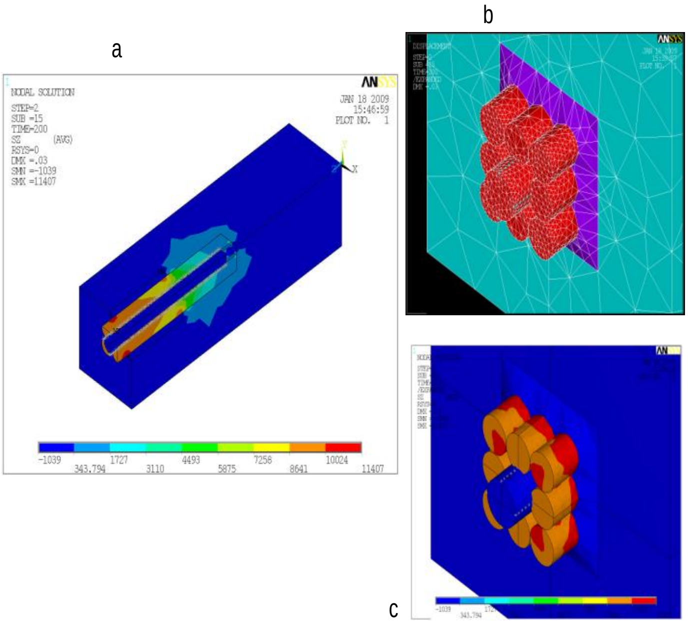


Figure 10. Nine glass fibers pull-out. a- axial stresses distribution in z-direction; b-deformation shape; c-axial stresses distribution in z-direction.

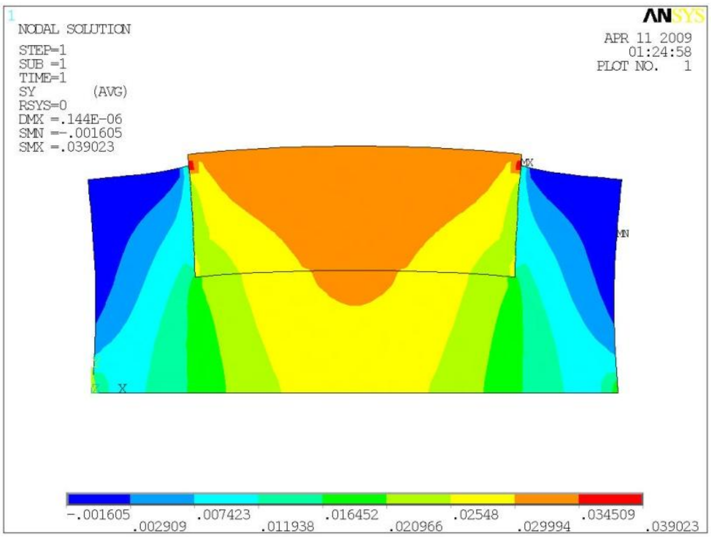


Figure 11.a. Stresses in the concrete and the fibers in a case of 800 filament bundle with perfect bond between outer fibers and concrete and weak bond between fibers in the bundle core. Stress in direction along fibers.

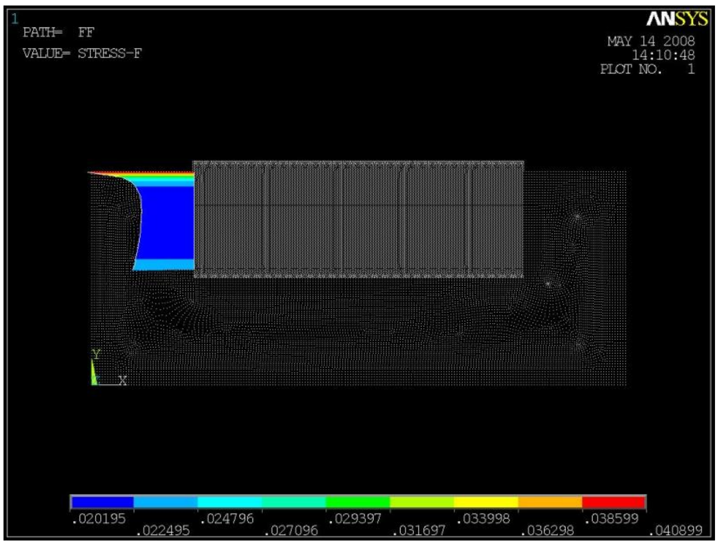


Figure 11.b. Stresses in the concrete and the fibers in a case of 800 filament bundle with perfect bond between outer fibers and concrete and weak bond between fibers in the bundle core. Tensile stress in outer fiber of the bundle.

5 FEW FIBERS PULL-OUT EXPERIMENTS

While fiber bundle pullout mechanism was recognized as the main micro-mechanical mechanism of post-cracking fiberconcrete behavior few fiber's pull-out experiments were realized with the goal to understand and appreciate fiber bridging effect in fiberconcrete post cracking behavior (see Figure 12).

Figure 12. Pull-out experiments for few fibers bundles (glass and carbon).

6 CONCLUSIONS

3D and 2D numerical investigations for non-metallic (glass, carbon) single fiber pull-out of concrete matrix were performed. Simulations results were com-pared with performed pull out experiments. Main fiber load bearing and rupture mechanisms were recognized: a) fiber rupture out of concrete; b) debonding growth along interface fiber/matrix; c) fiber rupture close to the tip of cylindrical debond crack in concrete and after that fiber end pulling out of concrete matrix with friction. Comparison al-lowed to obtain numerical values for micromechanical process- friction coefficients on the fiber/matrix interface during fiber sliding motion with friction out of concrete matrix.

7.ACKNOWLEDGEMENTS

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