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Numerical 3D Investigation of Non-Metallic (Glass, Carbon) Fiber Pull-out Micromechanics (in Concrete Matrix)

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Abstract **- In the paper short glass and carbon fiber micro-mechanics in concrete matrix is under consideration. In present work was performed pull-out 3D numerical modeling. Numerical results were compared with realized experiments for single and few (fibre bundle) AR glass and carbon fibers pulling out of concrete matrix. Investigated were one fiber pull-out dynamics as well micro-stresses in the material. During performed single fiber pull out experiments were established such process mains steps: a) fiber and matrix elastic deformation with perfect bond between fiber and matrix; b) cylindrical delamination crack growth in material between fiber and concrete matrix; c) fiber break in concrete, after what free fiber end with friction is pulling out of matrix. Numerical model based on FEM were elaborated for all three failure steps. Numerical simulations were established mechanical background for such failure phenomena. Were established main load bearing and failure mechanism for short glass and carbon fiber concrete composites – single fiber pull out with simultaneous fiber failure.**

Keywords **- glass and carbon fibres, concrete, fiber bundles.**

I. INTRODUCTION

Plain concrete is brittle, addition a short randomly distributed fibers lead to quasi-plastic 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 fibres are bridging crack surfaces; b) fiber bundles (of different size) are bridging crack surfaces. In present paper, investigations of single and few nonmetallic fibers micro-mechanics embedded into concrete matrix under external loads were performed numerically using 3D FEM approach.

II. SINGLE FIBER PULL-OUT MICROMECHANICS

Corresponding to investigation performed in [2], it is clear that the pull-out test 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. We are starting with the first one. The 3D situation is under investigation through creating a finite element model as shown in Figure 1.

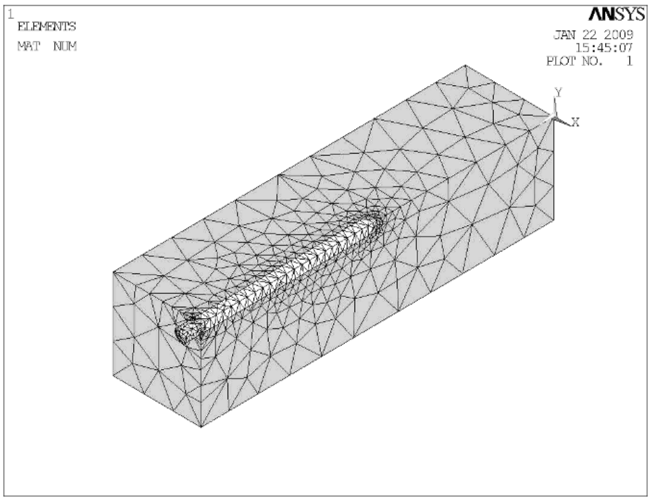


Fig. 1. 3D finite element model of single glass fiber embedded into the concrete matrix. Fiber is pulling out by external load, bond between fiber and matrix is perfect

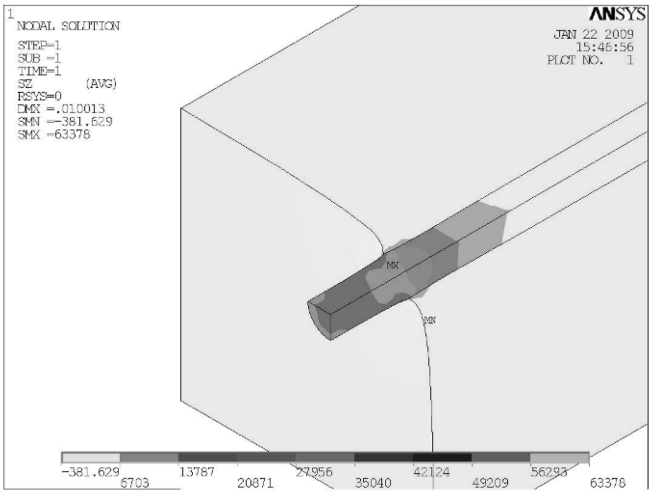
The material properties are similar as in the 2D situation [2]:

Concrete matrix: (E = 30000 MPa , υ = 0.2);

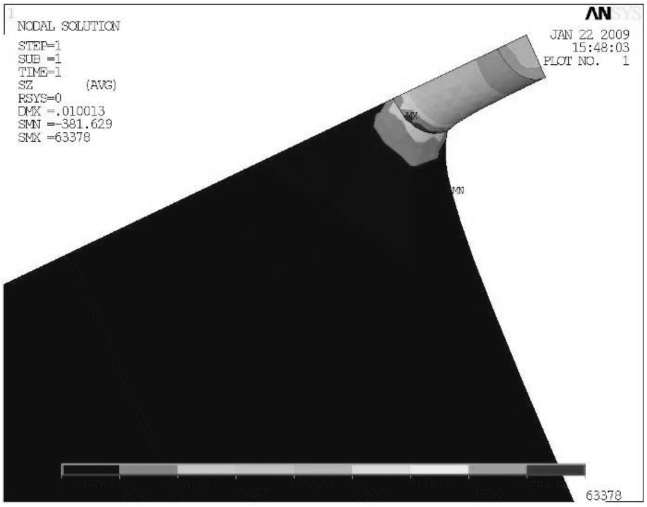
Glass fiber: (E = 70000 MPa , υ = 0.2).

„Soft“ material (corresponds to interlayer in fiber/concrete matrix debonded zone (see Fig. 3.a)): (E = 500-3000 MPa, υ= 0.25).

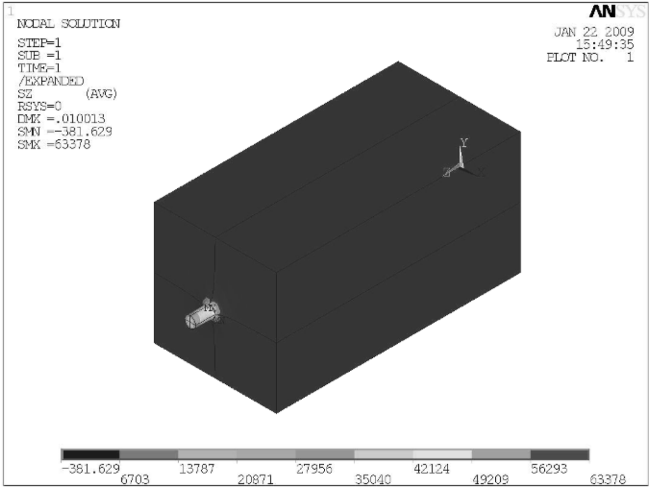
Fiber is pulling out of the concrete. Longitudinal stresses (z –direction) in concrete, in the case of perfect interface bond between fiber and matrix.(concrete) are shown in Figures 2 (a-d). Stress contours of the axial stresses in z- direction show that maximum stresses appear to be close to the connection region at the front surface, where the fiber emerges from the concrete matrix, while extracting the fiber from the matrix under tension applied load, what is the real reason to cut the fiber at this place where the fiber cross-section has the maximum axial stresses (such results were obtained in our experiments). If it is not happening we have a pull-out scenario. According to pull-out stages illustration, future pull-out force increase leads to debond 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 this case it is convenient to introduce thin “soft interlayer” between matrix and fiber, on the length of cylindrical debond in the material (see Fig. 3.a).



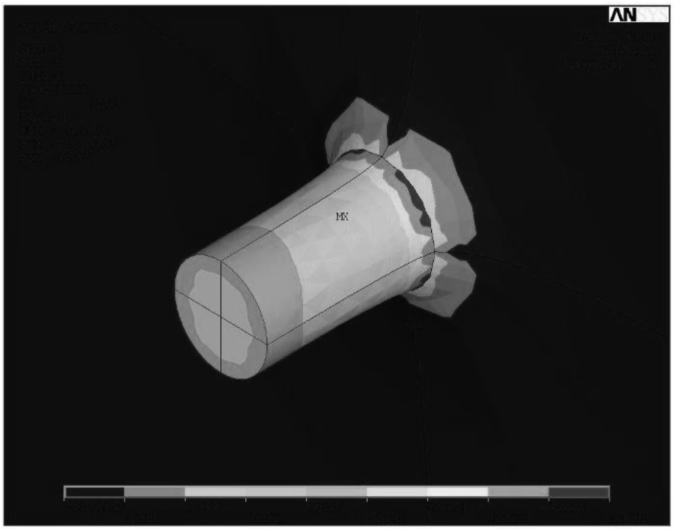
a)



b)



c)



d)

Fig. 2.(a-d) The axial stresses in z-direction of single glass fiber embedded into concrete matrix. 3D situation at the first stage of pull-out test. Fiber is perfectly bonded with matrix (concrete)

Really it is partially destroyed concrete matrix (fulfilled with cloud of micro-cracks). Created finite element model (mesh) is shown at Fig. 3.b. Numerical calculations were shown existence of two dangerous crossections in the fiber: first –at the outer surface of concrete matrix (where fiber is coming from the concrete) and second at the end of debonding zone (see Fig. 3.c-d). Stresses in fiber along the line parallel to fiber axis in vicinity to interface with matrix (0.98 of fiber radius) are shown In Fig. 3.d-e and in the matrix (r=1.02R) at Fig. 3.f. At Fig. 3.e. (2D calculation) 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) (=25 × 7E-03 mm); c) outer surface of concrete block (x= 35 × 7E-03 mm) (right peaks).

At the same time debond (cylindrical crack) is tending to grow corresponding to shear stress peak existing on the tip of debond crack (see fig. 3.e. and fig. 3.f).

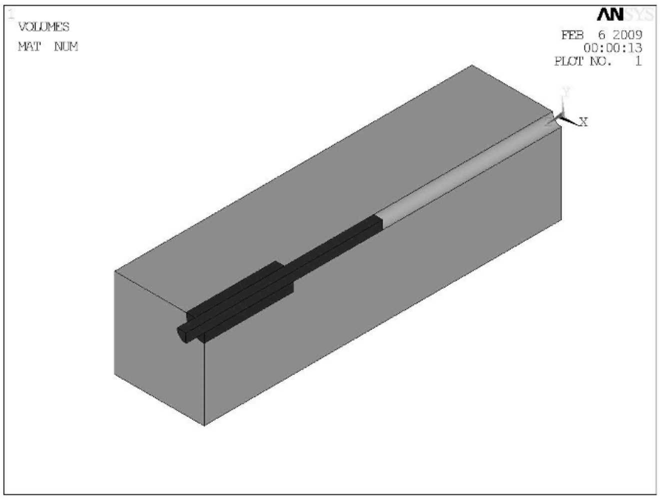


Fig. 3.a). Single glass fiber embedded into the concrete matrix. Fiber is partially debonded and is pulling out by external load

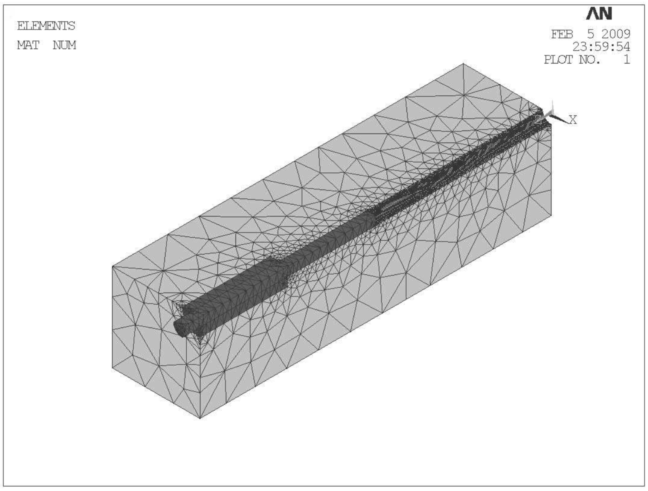


Fig. 3.b). 3D finite element mesh for single glass fiber embedded into the concrete matrix and partial debond between them.

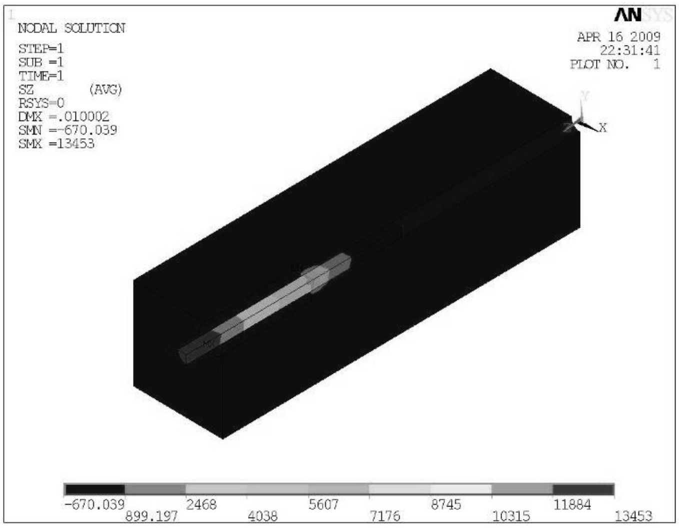


Figure 3.c). Axial (in fiber direction) stress distribution in partially debonded glass fiber and concrete matrix.

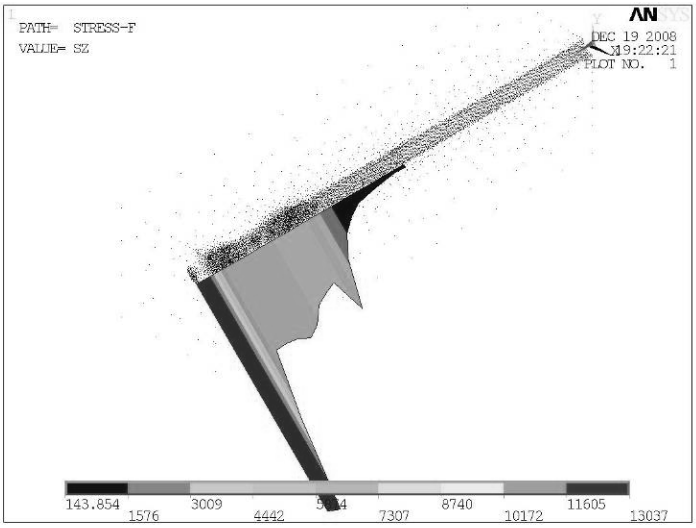


Fig. 3.d). Axial stress profile in the fiber (in fiber longitudinal direction) in partially debonded glass fiber (in concrete matrix) (3D calculation)

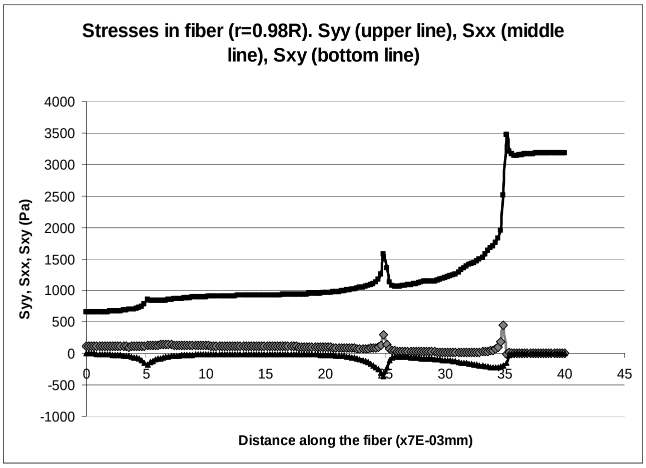


Fig. 3. e). 2D calculation (axisymmetric). Stresses in the fiber on the line parallel to fiber direction (r=0.98R). Stress in y direction along the fiber Syy (upper line), stress in x direction –direction orthogonal to fiber direction Sxx (middle line) and shear stress Sxy (bottom line).

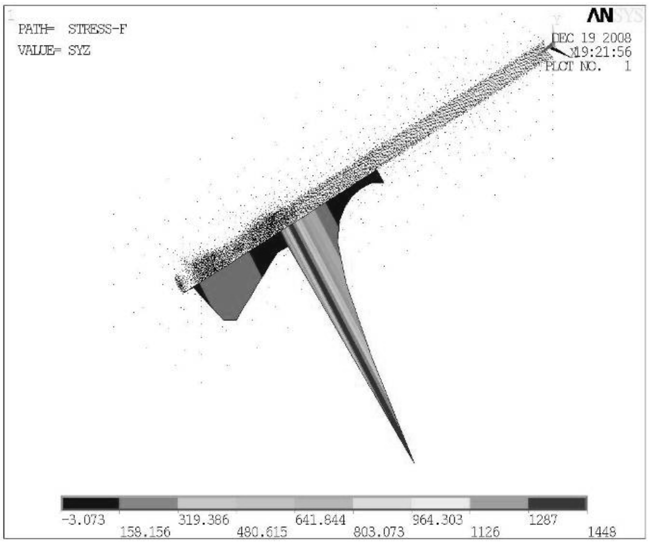


Fig. 3.f). Shear stress profile in the concrete matrix (stresses in the matrix on the line parallel to fiber direction (r=1.02R)) in the case of partially debonded glass fiber (in concrete matrix).

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); 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.d, e.) 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 (2D model) and 5 ((3D model).

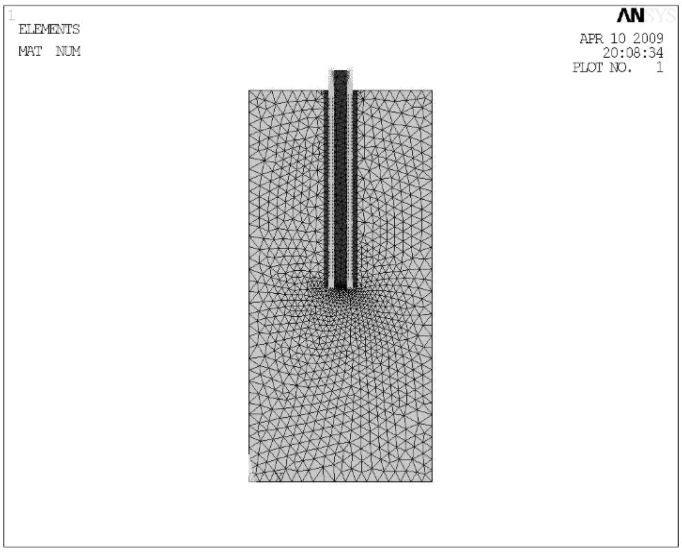


Fig. 4. 2D Fiber sliding motion numerical model. Between fiber and matrix are contact elements

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.c.and Fig. 6.a-b.).

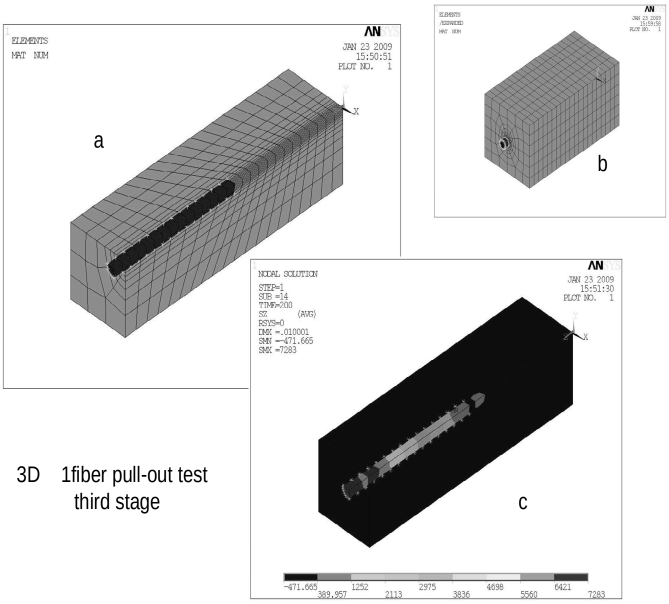


Fig. 5 a-c. Third stage of single glass fiber pull-out stage, where: a- finite element 3D model, b- closed finite element model, c- axial stresses distribution while frictional sliding motion.

III. EXPERIMENTAL VALIDATION

Obtained numerical results were validated by performed experimental tests (see Fig.7) for single glass and carbon fibers. Main fiber and matrix failure mechanisms were recognized. Single glass and carbon fibers were embedded into concrete matrix on the depth 10 mm and 20 mm. 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 fiber haven't exceeded 1.5 mm. This mechanism directly corresponds to pull out scenario and was modeled by models *b* and *c*.

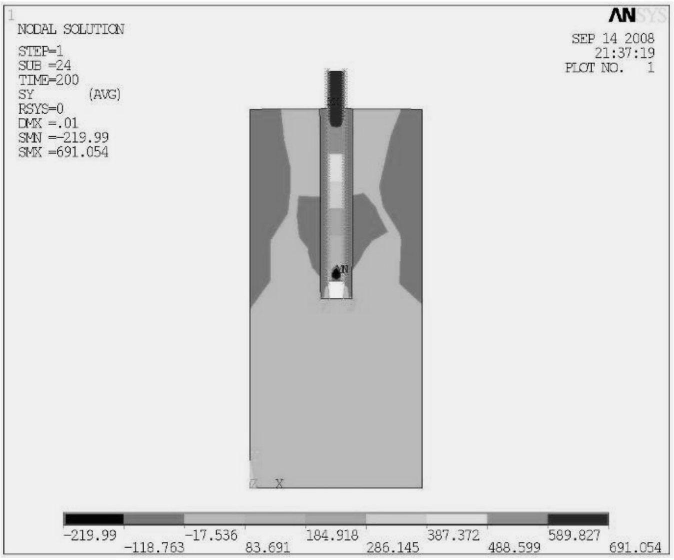


Fig.6.a. Fiber sliding motion numerical model. Between fiber and matrix are contact elements. Tensile stress y component (in fiber direction) in fiber and matrix, during starting stage of fiber pulling out with friction.

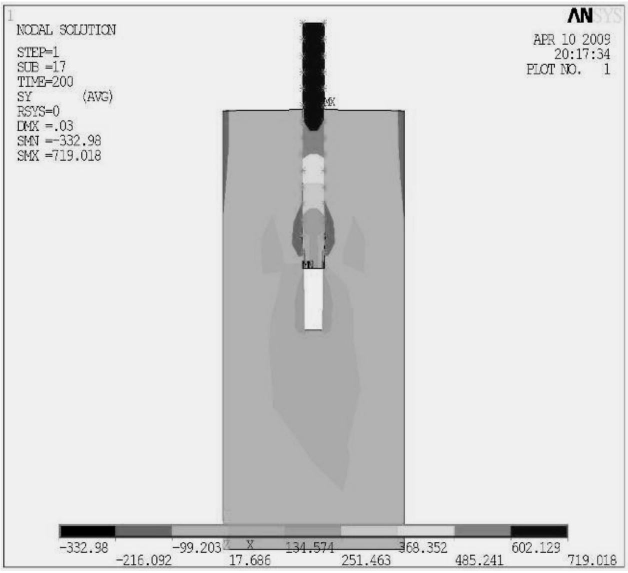


Fig. 6.b. Fiber sliding motion numerical model. Between fiber and matrix are contact elements. Tensile stress y component (in fiber direction) in fiber and matrix during middle stage of fiber pulling out with friction

During experiments were obtained two types of pull out force –pulling out displacement curves shown in Fig. 8 and Fig. 9. One set of curves corresponds to the case of fiber rupture out of concrete matrix (close to concrete surface, Fig.8). Another set of curves corresponds to the case of fiber/matrix debonding and fiber rupture inside the concrete block. After what fiber end with friction is pulling out. Experimental data comparison with numerical simulation allowed to obtain fiber critical length and fiber – matrix. Concrete mixes used in experiments were the same as in [1,2].

Fig. 7.a. Single fiber pull-out test view

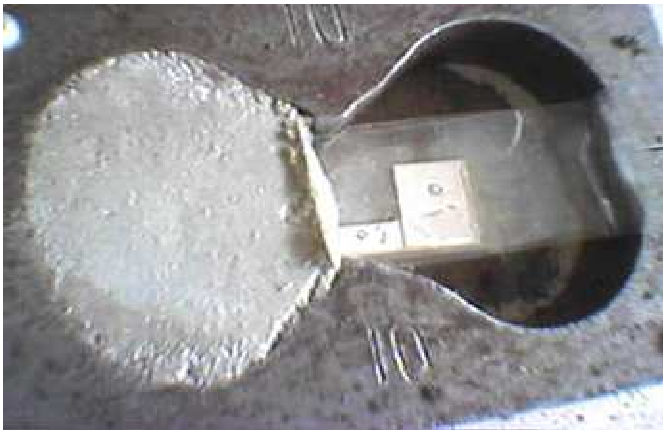


Fig. 7.b. Sample with embedded one glass fiber for single fiber pull-out test (common view)

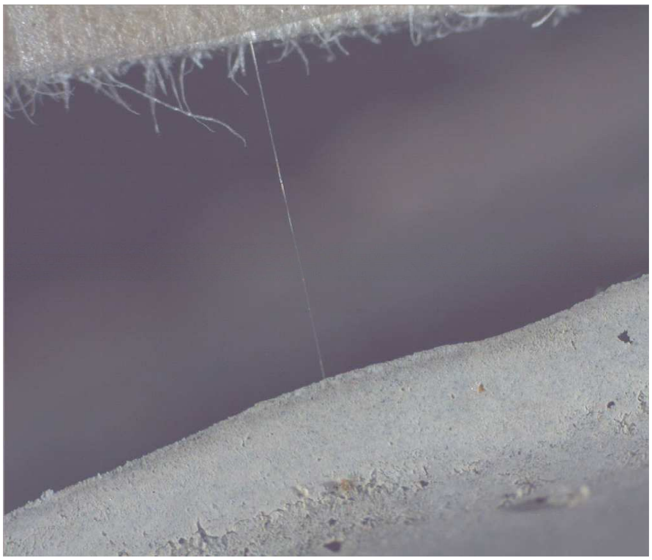


Fig. 7.c. Sample with embedded one glass fiber for single fiber pull-out test

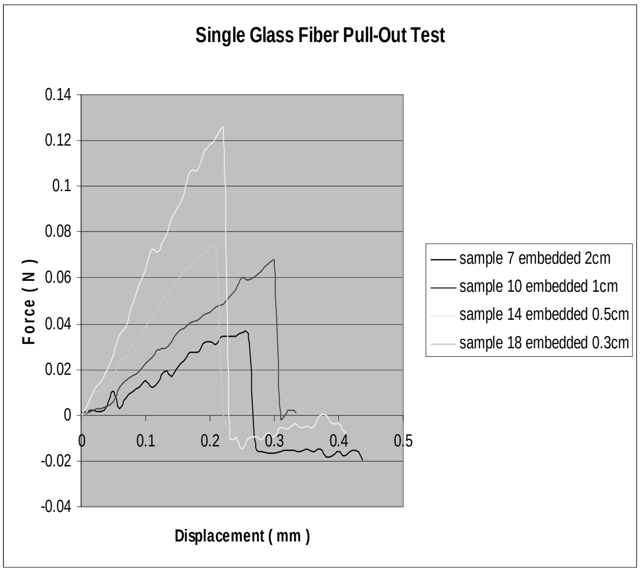


Fig. 8. Applied force (pulling out fiber) – grips mutual displacement curves corresponding to the case of fiber rupture out of concrete matrix (close to concrete surface)

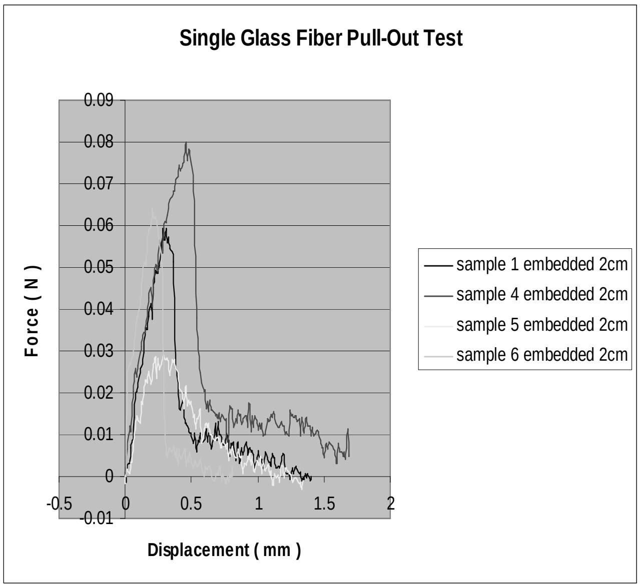


Fig. 9. Applied force (pulling out fiber) – grips mutual displacement curves corresponding to the case of fiber/matrix debonding and fiber rupture inside the concrete block. After what fiber end with friction was pulled out (horizontal part of post peak part of the curves)

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 0.12-0.20.

IV. CONCLUSIONS

3D and 2D numerical investigations for non-metallic (glass, carbon) single fiber pull-out of concrete matrix were performed. Simulations results were compared 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 allowed obtaining numerical values for micromechanical process- friction coefficients on the fiber/matrix interface during fiber sliding motion with friction out of concrete matrix.

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Andrejs Krasnikovs, Amjads Khabazs, Inese Telnova, Arturs Mačanovskis, Jānis Kļaviņš. Nemetālisko šķiedru (stikla, ogļekļa) izraušanas mikromehānikas (betona matricā) 3D skaitliskā analīze

Publikācijā tiek aplūkota stikla un oglekļa vienas šķiedras mikromehānika betonā, radītie spriegumu mikrolauki un izraušanas gaita ar atslāņošanas mehānismiem un izvilkšanas ainu. Veicot šķiedru izraušanas eksperimentus, tika konstatētas šā procesa fāzes: a) elastīgā šķiedras un betona deformēšanās bez destruktīviem procesiem; b) cilindriskā atslāņojuma augšana, startējot no betona virsmas un virzoties gar šķiedras un betona robežvirsmu; c) šķiedras gala noplīšana betonā un tā izvilkšana ar berzi. Visiem trim posmiem tika izveidoti skaitliski (GEM) trīs dimensionālie 3D modeļi. Veicot skaitlisku modelēšanu 3D un 2D, noskaidroti mehāniskie cēloni tādam sabrukšanas veidam. Tika konstatēts, ka galvenais plīsušā (betona ar makro-plaisām) betona slodzes nešanas mikromehānisms ir šķiedru daļēja pārraušana un izvilkšana no betona.

Андрей Красников, Амяд Хабаз, Инесе Тельнова, Артур Мачановский, Янис Клявиньш. Численное 3D исследование микромеханики выдергивания (из бетонной матрицы) неметаллических (стеклянных и углеродных) волокон

В работе рассмотрена микромеханика коротких стеклянных и угольных волокон в бетонной матрице. Исследовались динамика вытаскивания и поля напряжений вокруг одного волокна вытягиваемого из матрицы. Были установлены основные этапы процесса: а) совместное деформирование матрицы и волокна; б) рост отслоения (цилиндрической формы) между волокном и матрицей; в) разрыв волокна в бетоне с последующим вытаскиванием (с трением) оторванного конца из бетона. Численные модели 3D и 2D описывающие все три стадии (базирующиеся на МКЭ) были созданы. Проведенное численное моделирование позволило выяснить причины доминирования разрушения материала механизмом выдергивания волокон. Проведенный анализ выявил роль отдельных волокон и объяснил их поведение в растрескивающемся фибробетоне.