

**NUMERICAL 2D INVESTIGATION OF NON-METALLIC (GLASS, CARBON) FIBER  
MICRO-MECHANICAL BEHAVIOR IN CONCRETE MATRIX**

**BETONA MATRICĀ IEVIETOTO NEMETĀLISKO ŠĶIEDRU (STIKLA, OGŁEKŁA)  
MIKRO-MEHĀNISKĀS UZVEDĪBAS 2D SKAITLISKĀ ANALĪZE**

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## Introduction

Plain concrete has brittle nature of results in its poor resistance to crack propagation. Inclusion the short dispersed fibers in concrete help to prevent a catastrophic type of failure by transferring the stresses across a cracked matrix. Fibers are bridging each crack resulting to quasi-plastic material post cracking behavior.

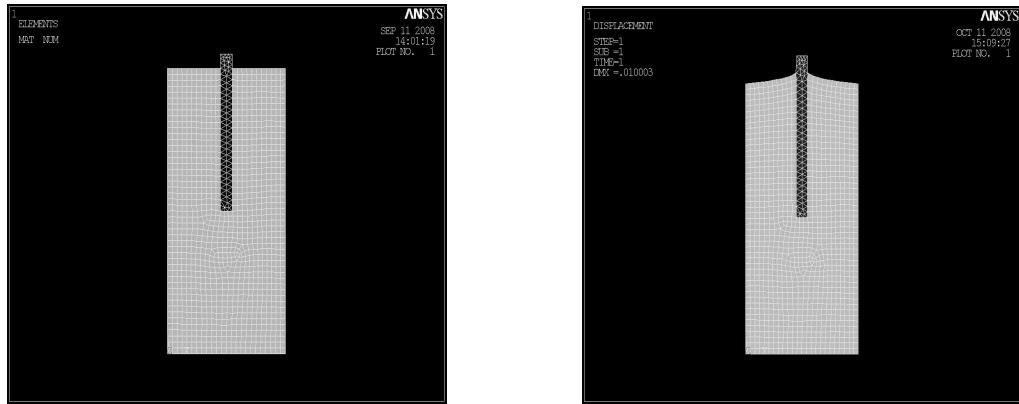
That is why properties of the fiber-matrix interface are of primary significance for the overall behavior of fiber concrete. If we want to predict fiber concrete material cracking and post-cracking behavior, and the same time are looking for tensile strength increase and quasi-plastic (with few % deformation without loosing load bearing capability) material post-cracking behavior, the study of fiber/matrix interfaces in cement based composites 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. Interpretations of interface bond micro-mechanical properties were done by Stang [5], Li [6], Li et al. [7] and Stang et al. [8].

Fracture experimental investigation for glass and carbon short fiber concretes [9] 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, investigation of single and few non-metallic fibers micro-mechanics embedded into concrete matrix under external loads were performed numerically using 2D FEM approach.

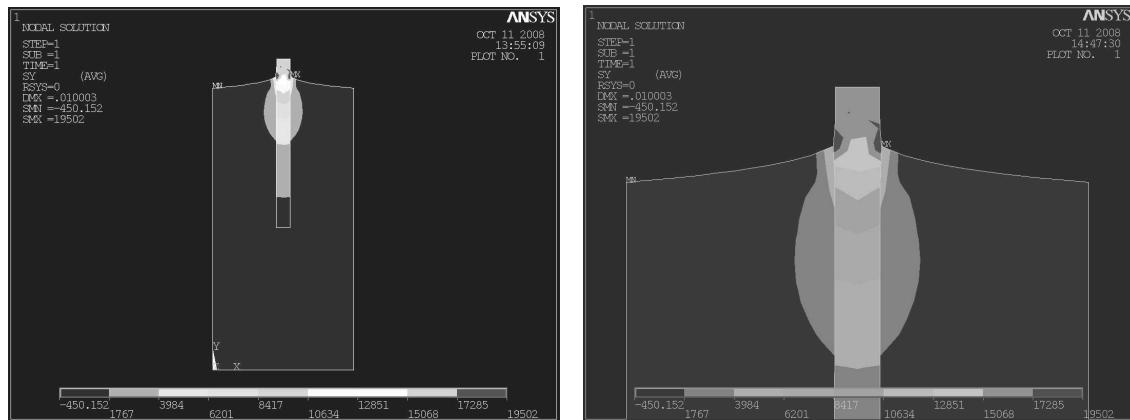
## Single fiber pull-out micromechanics

Single fiber is oriented orthogonal to concrete surface and is pulling out. Such situation is simulating the fiber is bridging crack's 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, 9]. External load is applied to fiber pulling it out of concrete matrix (see Fig.1). 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.



**Fig. 1.** Single fibre is embedded in concrete matrix. Fiber is pulling out by external load (before loading (a), and after (b)), bond between fiber and matrix is perfect

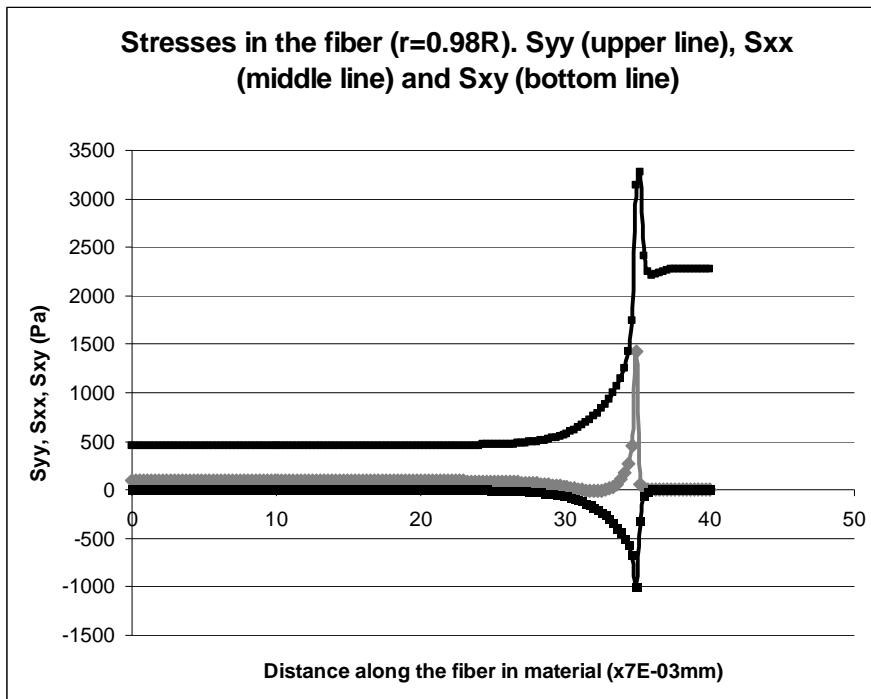


**Fig. 2.** Stress in Y (vertical) direction in fibre and concrete matrix. Single fibre is embedded in concrete matrix with perfect bond between them (common view (a), area of maximal tensile stresses (b))

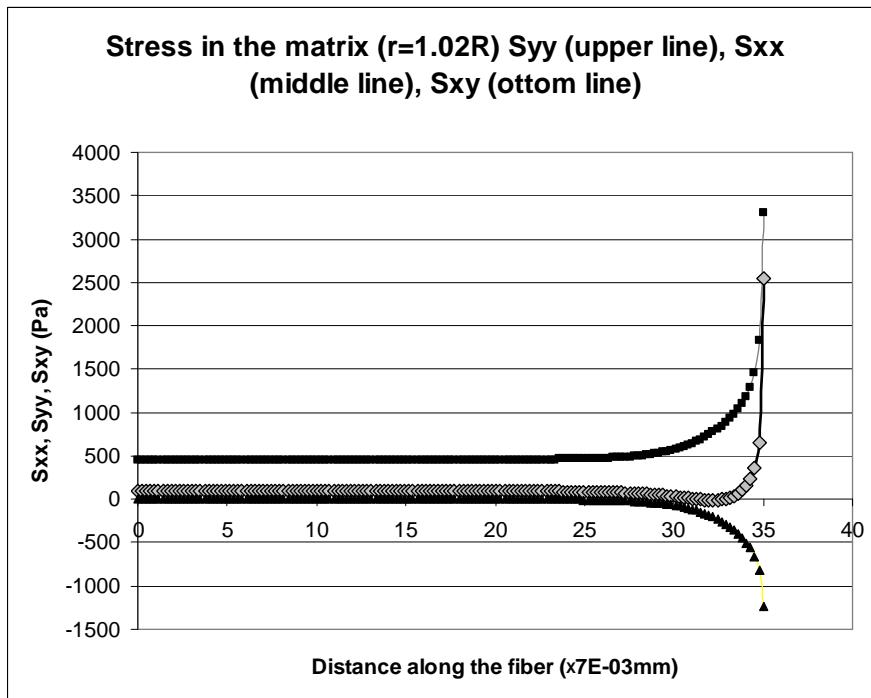
Fibers breaking in material according scenario a-c are responsible to fiberconcrete post-cracking quasi-plastic behaviour and are the subject of present investigation. Simulations have been done by ANSYS structural program with mechanical properties of materials:

concrete matrix:  $E = 30000 \text{ MPa}$ ,  $\nu = 0.2$ ; AR Glass fiber:  $E = 70000 \text{ MPa}$ ,  $\nu = 0.2$ ; Carbon fiber:  $E = 300000 \text{ MPa}$ ,  $\nu = 0.2$ ; Interlayer:  $E = 500-3000 \text{ MPa}$ ,  $\nu = 0.25$ .

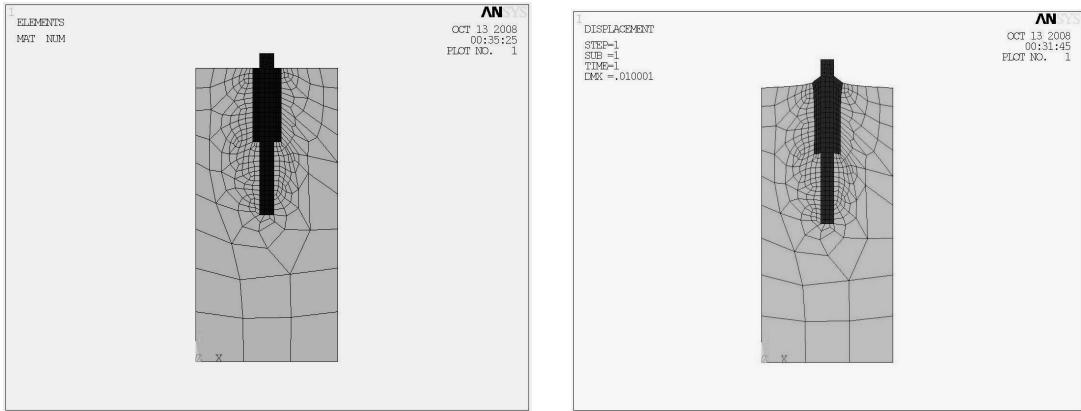
Three numerical 2D models were under investigation. First: single glass (carbon) fiber is embedded into concrete matrix with perfect bond between them and subjected to external pulling load (see Figure 1). Axial stress contours in Y direction (vertical) in concrete and matrix are shown in Figure 2. Maximal tensile stress in stretched fiber is concentrated in crosssection coinciding with concrete outer surface (see Fig.2,3). Similar situation is with shear stress on the interface between matrix and fiber (see Fig.2,4). Horizontal coordinate  $x=35*7E-03\text{mm}$  corresponds to concrete surface.  $R (R=7E-03\text{mm})$  is the fiber radius.



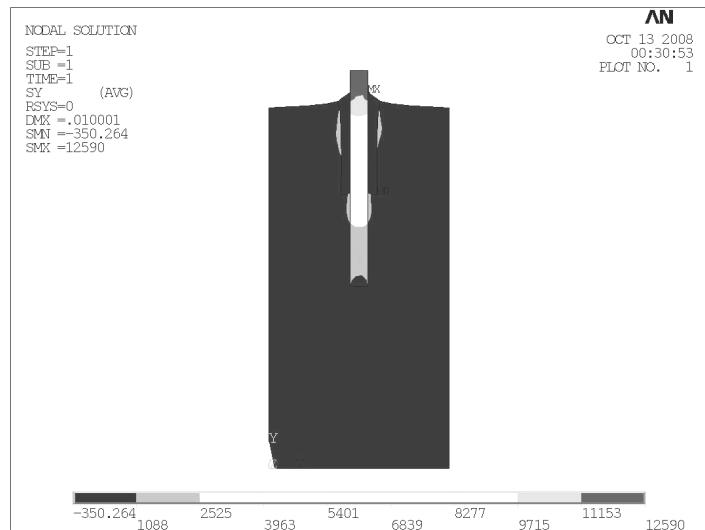
**Fig. 3.** Stresses in the fiber in vicinity of fiber/matrix interface ( $r=0.98R$ ). Between fiber and matrix is perfect bond. Syy -upper line; Sxx-middle line; Sxy-bottom line



**Fig. 4.** Stresses in the matrix in vicinity of fiber/matrix interface ( $r=1.02R$ ). Between fiber and matrix is perfect bond. Syy -upper line; Sxx-middle line; Sxy-bottom line

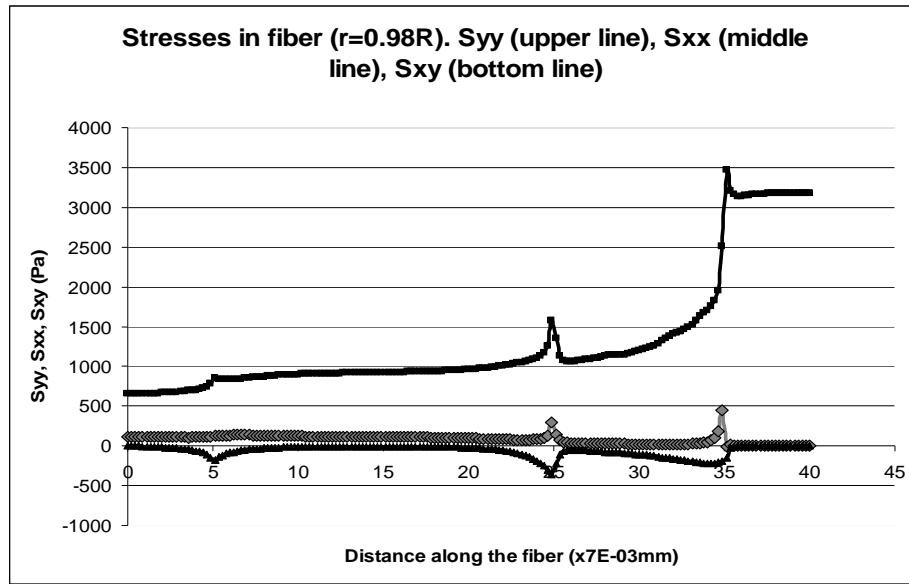


**Fig. 5.** Between pulling out fiber and matrix is growing delamination which is simulated by soft interlayer (before loading (a), and after (b))

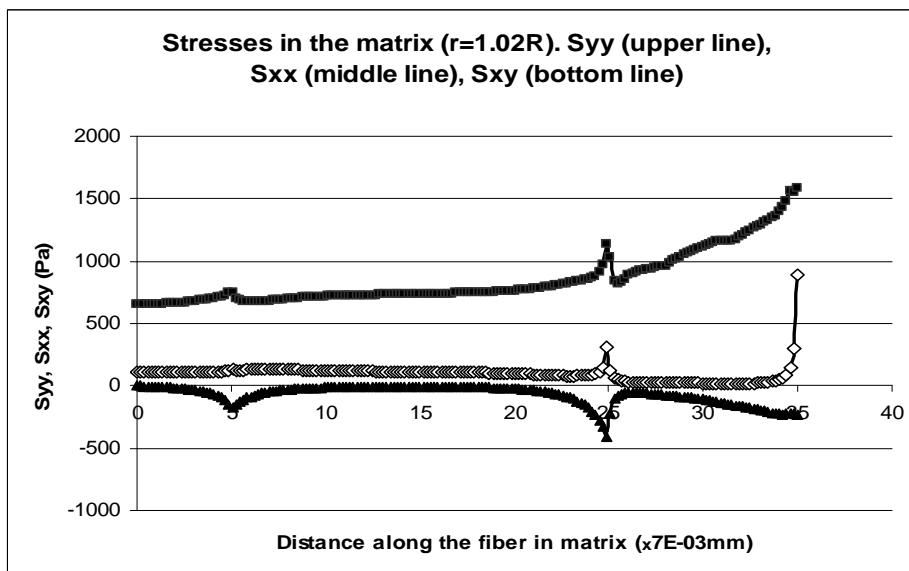


**Fig. 6.** Stress in vertical direction in fibre and concrete matrix. Between pulling out fiber and matrix is growing delamination which is simulated by soft interlayer

Second model is describing the situation, when between 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 (see Fig. 5). Axial stress contours in Y (vertical) direction in concrete and matrix are shown in Fig. 6. 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.7 and in the matrix ( $r=1.02R$ ) at Fig.8. 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 ( $x= 35*7E-03mm$ ). 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 concrete block) surface and increase of fiber/matrix interface friction (corresponds to concrete matrix with higher compressive strength). These contrary factors are describing possibility to introduce “critical length” –parameter characterized fiber anchoring capacity. At the same moment overloads in the matrix are rising into concrete body micro-cracks formation around the fiber (see Fig. 9,10). These cracks were observed experimentally.

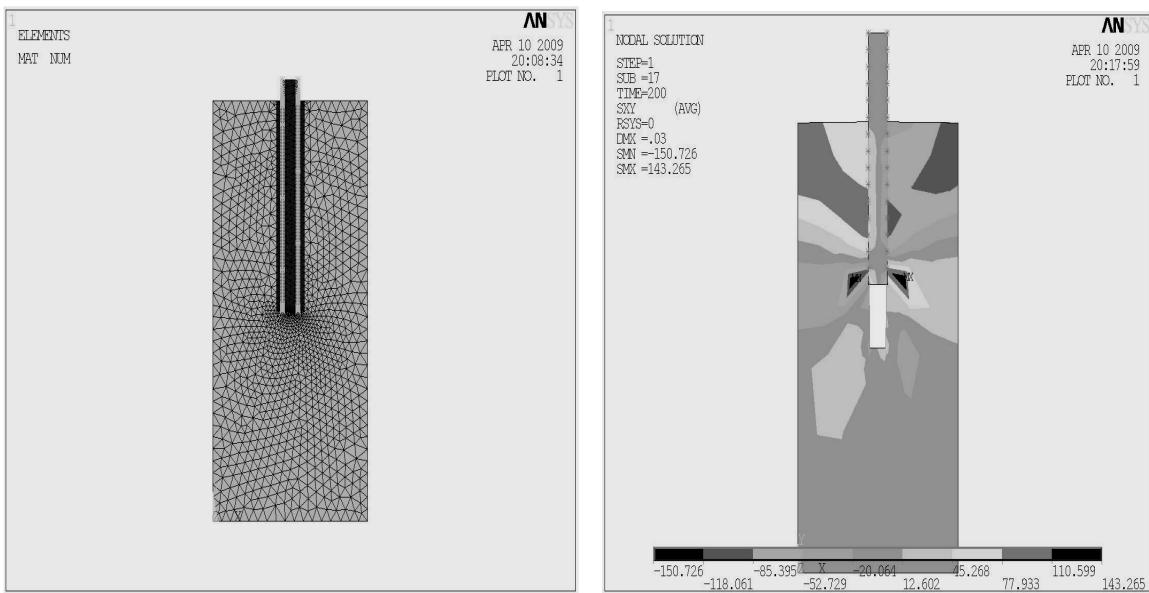


**Fig. 7.** Stresses in the fiber on the line parallel to fiber direction ( $r=0.98R$ ). Stress in y direction along the fiber Syy (upper line), stress in x direction –direction orthogonal to fiber direction Sxx (middle line) and shear stress Sxy (bottom line)

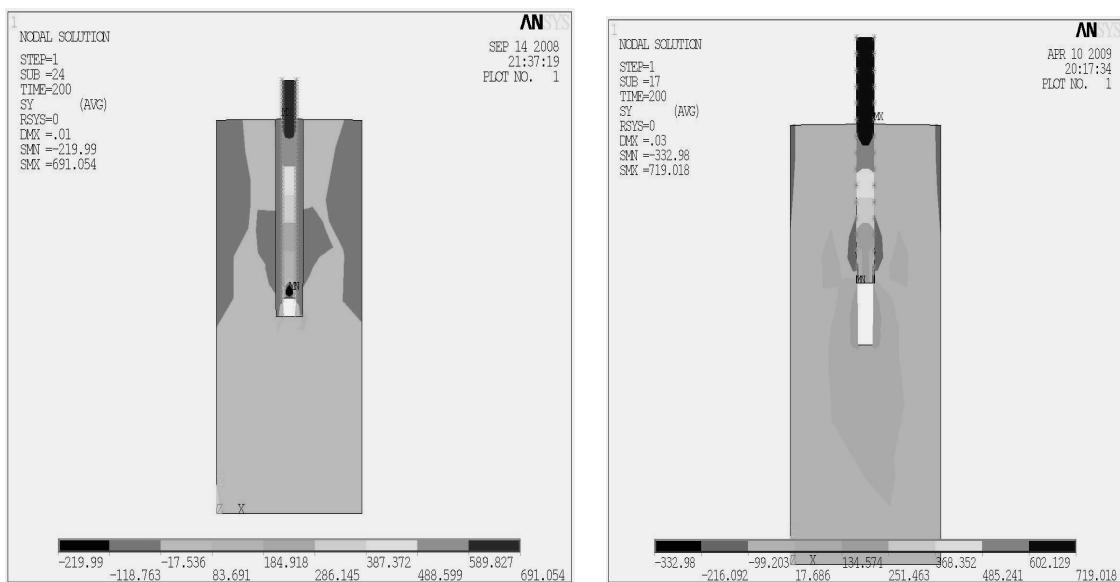


**Fig. 8.** Stresses in the matrix on the line parallel to fiber direction ( $r=1.02R$ ). Stress in y direction along the fiber Syy (upper line), stress in x direction –direction orthogonal to fiber direction Sxx (middle line) and shear stress Sxy (bottom line)

Third numerical model were elaborated to describe fiber sliding motion after the break in concrete matrix or delamination reach the embedded end of fiber. FEM model with contact elements between fiber and matrix were exploited (see Fig. 9.).



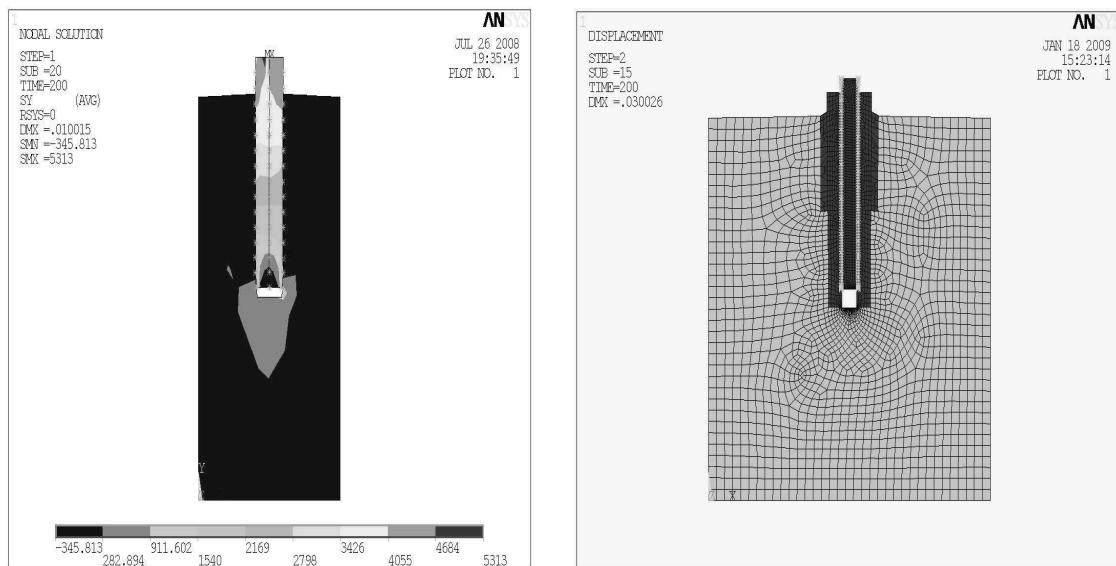
**Fig. 9.** Fiber sliding motion numerical model. Between fiber and matrix are contact elements (left picture). Shear stress in fiber and matrix during siding motion (right picture)



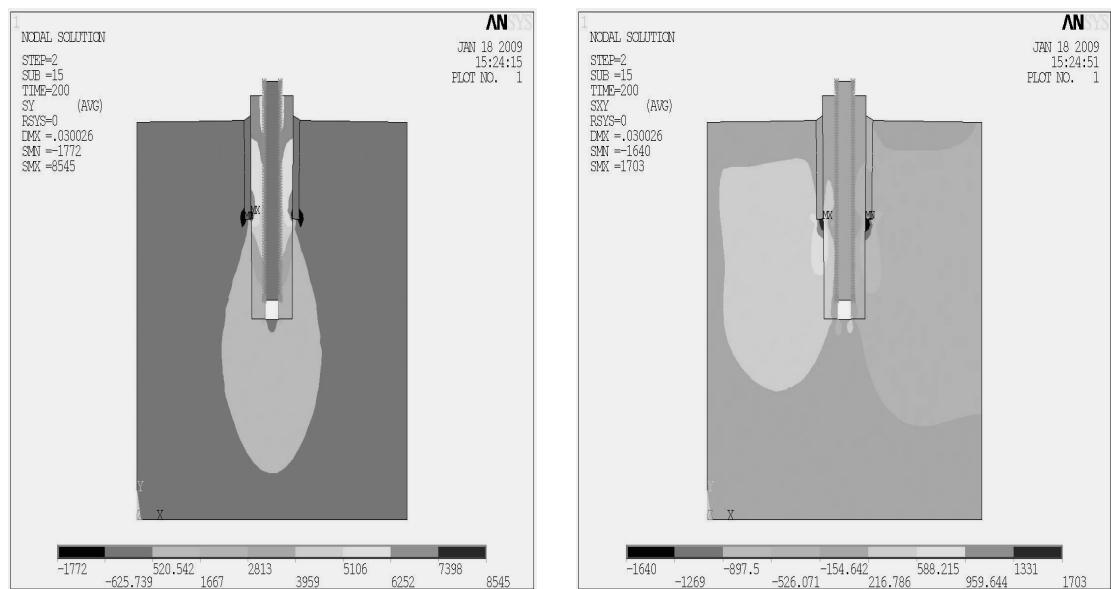
**Fig. 10.** Tensile stress y component (in fiber direction) in fiber and matrix during different stages of fiber pulling out with friction

### Small fiber bundle 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. 11,12,14.



**Fig. 11.** Tensile stress y component (in fibers direction) in the case of sliding motion of 2 fibers with different friction on the interfaces fiber/matrix and fiber /fiber (left picture). Three fiber pull out in the case of delamination and sliding with friction of internal fiber (right picture)

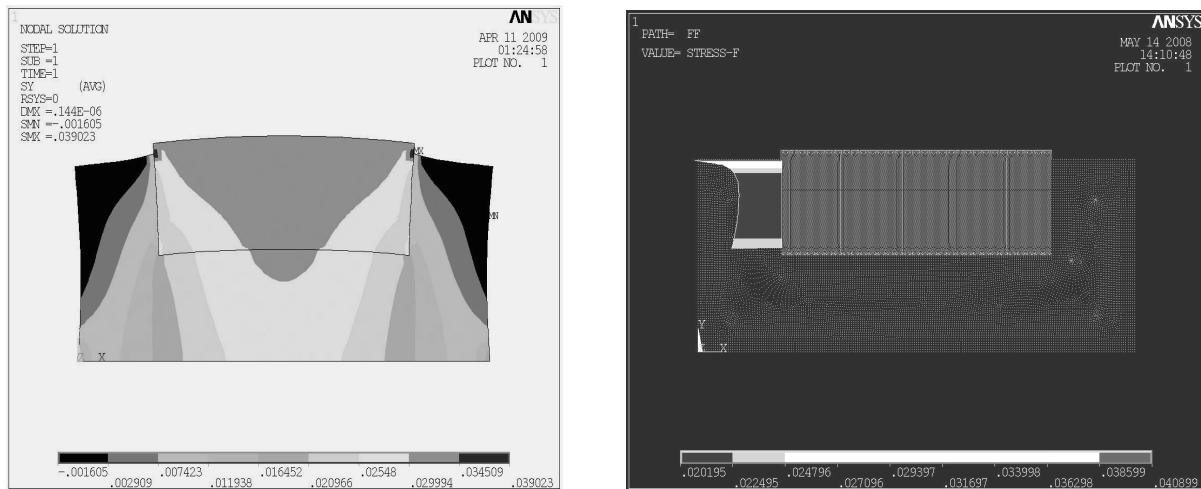


**Fig. 12.** Stresses in concrete and fibers in the case of delamination and internal fiber sliding motion with friction. Axial (y direction) stress (left picture). Shear stress (right picture)



**Fig. 13.** 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)

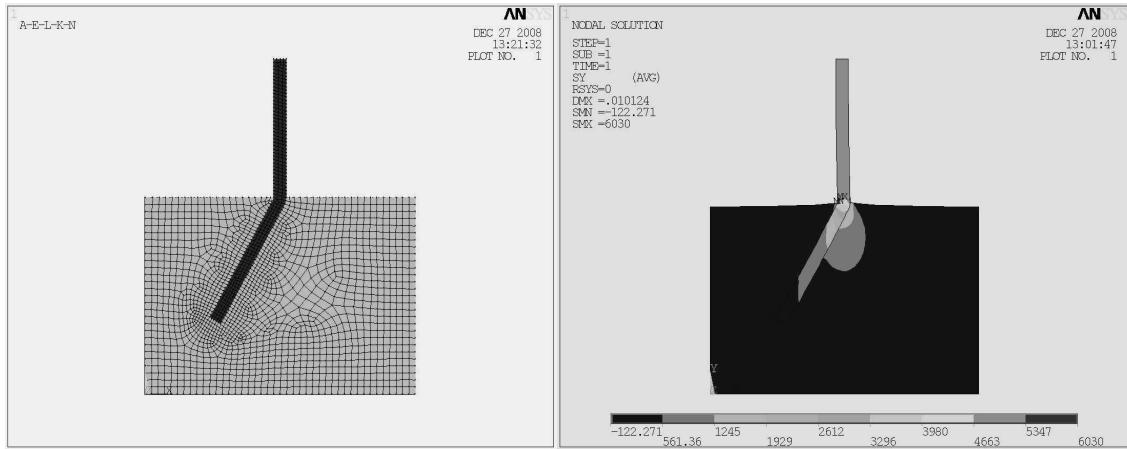
Traditionally non-metallic (glass, carbon) short fibers are ready for concrete mix available in a form of fiber bundles (chopped strands) with 600 to 1200 filaments in each bundle. During fiberconcrete mixing cement paste are penetrating into bundles only partially, forming external shell (composite 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.13. Looking on stress profiles (Fig.14) 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.



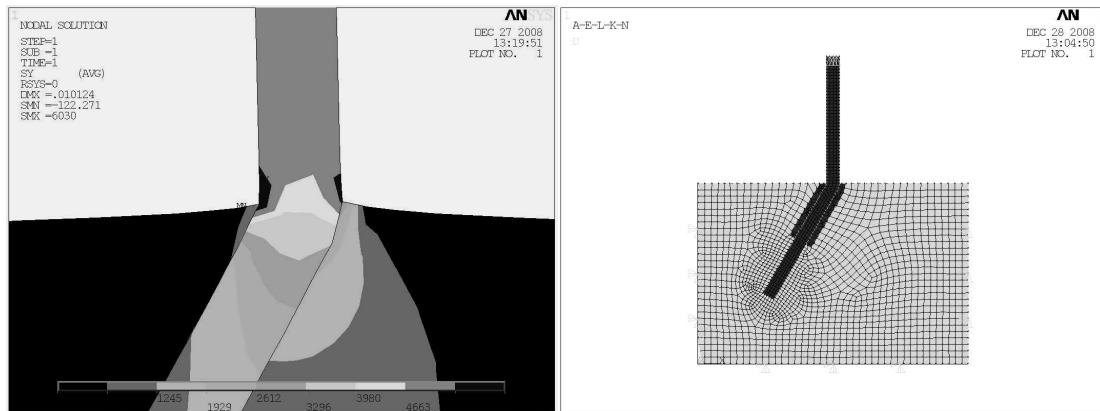
**Fig. 14.** Stresses in the concrete and the fibers in a case of 800 filament bundle with perfect bond between outer fibers and concrete and week bond between fibers in the bundle core. Stress in y direction Syy (left picture). Stress Syy in outer fiber of the bundle (right picture)

## Single glass fiber pulling out under angle

It's obvious that fibers are crossing crack surface under different angles (see Fig. 13, 15).

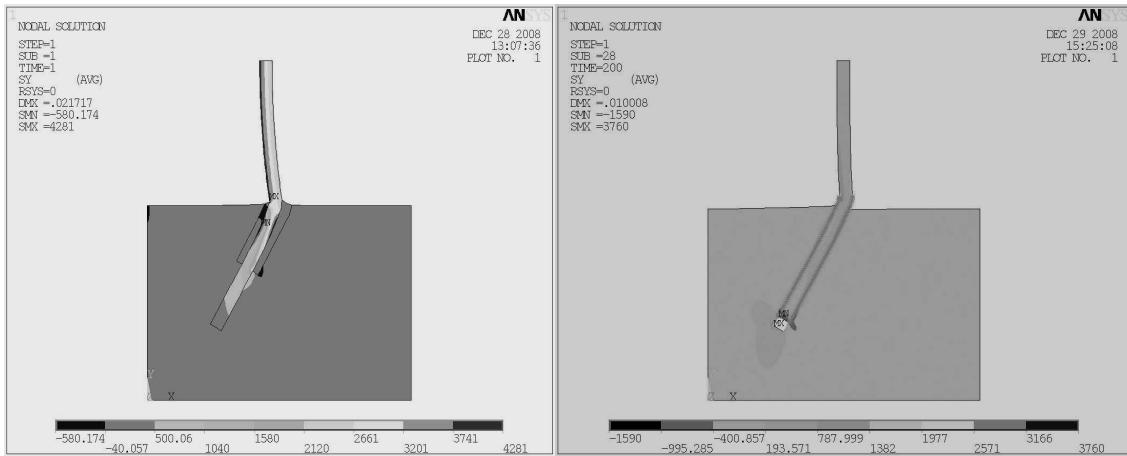


**Fig. 15.** Single fiber pull-out under angle  $\alpha = 30^\circ$  to concrete surface. Perfect bond between fiber and matrix. Stress in y direction (right picture)

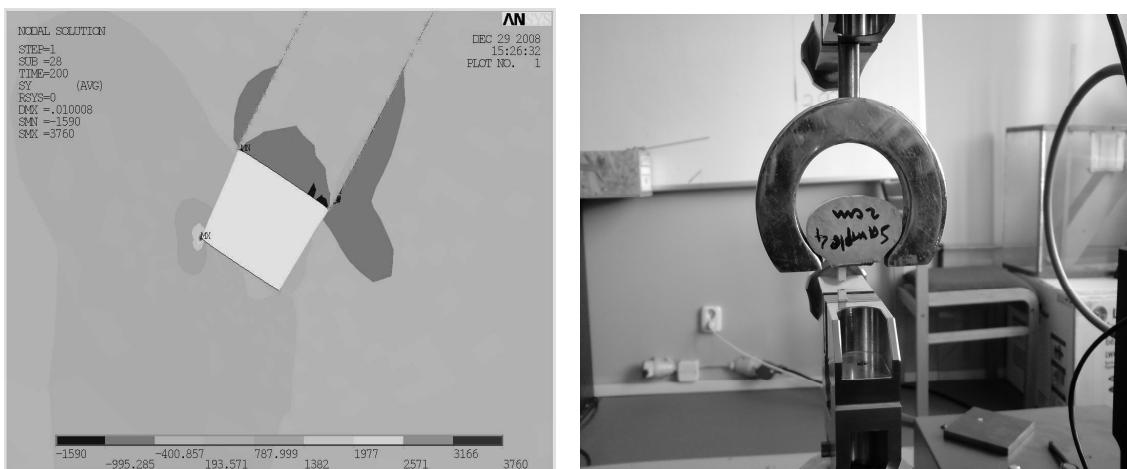


**Fig. 16.** Single fiber pull-out under angle  $\alpha = 30^\circ$  to concrete surface. Perfect bond between fiber and matrix. Stress in y direction (left picture). Fiber with partial delamination (right picture)

Numerical simulations were performed for single fiber pull out under angle  $\alpha \in [0^\circ, 70^\circ]$  to concrete surface, according models: with perfect bond between concrete and fiber; with partial debonding and sliding. Results for  $\alpha = 30^\circ$  are shown in Fig. 15-18. Stress pictures show us rupture possibilities for single fibers bridging cracks: if bond between fibre and matrix is perfect, one part of fibers are breaking in crossection coinciding with concrete surface (Fig. 15, 16). At the same time stresses in concrete are tending to cut concrete. Delamination started and for inclined fiber in concrete, with partial debonding, overloads are going (Fig. 14) inside the concrete block (similarly like for straight fiber). Fiber sliding leads to origination of micro-cracks in concrete around empty fiber channel in concrete.



**Fig. 17.** Single fiber pull-out under angle  $\alpha = 30^\circ$  to concrete surface. Fiber with partial delamination, stress in y direction (left picture). Fiber sliding with friction (right picture)



**Fig. 18.** Single fiber pull-out under angle  $\alpha = 30^\circ$  to concrete surface. Fiber sliding with friction. Overstress in the matrix (left picture). Pull out experimental investigation (right picture)

## Experimental validation

Obtained numerical results were validated by performed experimental tests (see Fig.18) for single, 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 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).

## Conclusions

2D 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.

## Acknowledgements

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## Krasnikovs A., Khabazs A., Kononova O., Nemetālisko šķiedru (stikla, oglekļa) betona matricā mikromehāniskās uzvedības 2D skaitliskā analīze

*Publikācijā tiek aplūkota stikla un oglekļa šķiedru mikromehānika betonā, tāda, ka vienas šķiedras, vai šķiedru kūļa radītie spriegumu mikro-lauki un izraušanas dinamika. Veicot šķiedru izraušanas eksperimentus tika konstatētas šā procesa fāzes: a) elastīgā šķiedras un betona deformēšanos bez destruktīviem procesiem; b) cilindriskā atslānojuma 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) modeļi. Veicot skaitlisku modelēšanu noskaidroti mehāniskie cēloni tādam sabrukšanas veidam. Analogiski ir izpētīti šķiedru kūļi un šķiedras iegremdētas betonā zem leņķa pret velkošo spēku. Tika konstatēts, ka galvenais plūsušā (betona ar makro-plaisām) betona slodzes nešanas mikro-mehānisms ir šķiedru izvilkšana un daļēja pārraušana kūļos, kuri armē betonu.*

## Krasnikovs A., Khabbaz A., Kononova.O. Numerical 2D investigation of non-metallic (glass, carbon) fiber micro-mechanical behavior in concrete matrix

*In the paper short glass and carbon fiber micro-mechanics in concrete matrix is under consideration. Investigated were one fiber or fibre bundle pullout dynamics as well micro-stresses in the material. During performed single fiber and single bundle pull out experiments were established such process mains steps: a) fiber and matrix elastic deformation with perfect bond between fibre and matrix; b) cylindrical delamination crack growth in material between fibre and concrete matrix; c) fibre 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. Similar way numerical models were elaborated and exploited for fibre bundles and single fibers were embedded into concrete under angle to pull out force direction. Were established main load bearing and failure mechanism for short glass and carbon fiber concrete composites – single fibre and fibre bundles pull out with simultaneous fibre failure in outer bundles shell.*

**Красников А., Хабаз А., Кононова О. Микромеханические и макромеханические свойства бетона армированного стеклянными и углеродными волокнами**

*В работе рассмотрена микромеханика коротких стеклянных и угольных волокон в бетонной матрице. Исследовались динамика вытаскивания и поля напряжений вокруг одного волокна или пучка волокон, вытягиваемых 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. Были созданы численные модели, описывающие все три стадии (базирующиеся на МКЭ). Проведенное численное моделирование позволило выяснить причины доминирования разрушения материала механизмом выдергивания волокон и пучков. Также исследовалась микромеханика выдергивания волокон, находящихся под углом к направлению выдергивания. Проведенный анализ выявил роль отдельных волокон в пучке и объяснил поведение пучка в растрескивающемся фибробетоне.*