plaisas virsmu. Aizpildot formu ar ASF, kuram ir pievienotas tērauda šķiedras, šķiedras tajā pārvietojas un griežas, kustoties kopā ar betona masu līdz kustības beigām betona ķermeņa katrā iekšējā punktā. Pie vienas un tās pašas formas aizpildes darot to no dažādiem galiem, var iegūt fibrobetona paraugus ar atšķirīgām iekšējām struktūrām (un ar atšķirīgu stiprību). Tika veikta plūsmas skaitliskā modelēšana (izmantojot Ņūtona un Bingama plūsmas modeļus), kā arī tika izpildīti vienas šķiedras plakanas kustības un griešanas skaitliski un eksperimentāli pētījumi viskozā šķidrumā. Tika iegūtas prizmatisku paraugu rentgena fotogrāfijas, kā arī ir izanalizētas šķiedru iekšējas pozīcijas un to orientācijas. Tāpat tika identificētas šķiedru pozīcijas un orientācijas plaisas šķērsgriezumā, un dotie rezultāti tika salīdzināti ar rezultātiem, kuri ir iegūti pie skaitliskas modelēšanas. ASF (kurš ir armēts ar tērauda šķiedrām) sabrukšanas strukturālais modelis tika noteikts uz vienas šķiedras izvilkšanas no matricas likumiem, kuri tika iegūti eksperimentāli. Modeļa noteikto parauga stiprību un plaisāšanas ainu pārbaudīja salīdzinot to ar četru punktu lieces eksperimentiem uz prizmām ar izmēriem 15 x 15 x 60 cm.

АБСТРАКТ

Несущая способность (и прочность) высокопрочного бетона, армированного стальными волокнами, зависит от числа волокон (соединяющих берега трещины), пересекающих слабейшую трещину и от их ориентации по отношению к поверхности трещины. При заполнении формы высокопрочным бетоном, армированным стальными волокнами, волокна перемещаются и вращаются, двигаясь вместе с бетонной матрицей до конца движения в каждой внутренней точке бетонного тела. При заполнении одной и той же формы с разных концов, могут быть получены образцы высокопрочного бетона, армированного стальными волокнами, с различными внутренними структурами (и с различной прочностью). Было выполнено численное моделирование потока (используя жидкостные модели Ньютона и Бингама), а также были выполнены численные и экспериментальные исследования плоского движения и вращения одного волокна в вязкой жидкости. Были получены рентгеновские снимки призматических образцов, а также проанализированы внутреннее расположение волокон и их ориентации. Также были идентифицированы позиции и ориентации волокон в поперечном сечении трещины, и данные результаты сравнивались с результатами, полученными при числовом моделировании. Структурная модель разрушения высокопрочного бетона, армированного стальными волокнами, была создана на основе законов вытягивания одного волокна из бетонной матрицы, которые были получены экспериментально. Численные прогнозы были подтверждены экспериментально на призмах с размерами 15 x 15 x 60 см, которые были протестированы на четырёхточечный изгиб.

Andrejs Krasnikovs, Vitalijs Lusis, Videvuds Lapsa, Vitalijs Zaharevskis, Edgars Machanovskis

CONCRETE SHELLS REINFORCED BY GLASS FIBERS

BETONA ČAULAS STIEGROTAS AR STIKLA ŠĶIEDRĀM

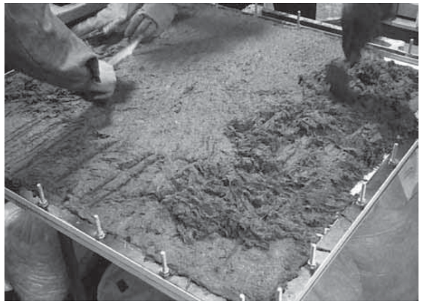
Key words:
glass and carbon fibre reinforced concrete, glass, carbon fibre bundles.

INTRODUCTION

Concrete is brittle material, if we want to fabricate thin wall (few centimetres) construction elements (thin wall shells) made out of concrete we are forced to use a small diameter densely placed reinforcement. One solution can be -short AR glass fibers homogeneously distributed in the concrete, another –few layers of knitted AR glass fibre fabrics (fulfilled by concrete) and placed at even distance one to another throw the thickness of the structure. Let start with short glass fibre concrete, If we want to predict fibre concrete material cracking and post-cracking behaviour, and at the same time are looking for material with elevated tensile strength properties and quasi-plastic (with few % deformation without loosing load bearing capability) material post-cracking behaviour, the study of single fibre and fibre bundle pull-out mechanisms out of cement matrix is important. Publications discussed this problem are described in [1-4]. Fracture experimental investigation for glass, steel and carbon short fibre concretes [1] was recognized main micro-mechanisms of fibre 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.

Another option is use of knitted AR glass fibre fabrics (fulfilled by concrete) and placed at even distance one to another throw the thickness of the structure.

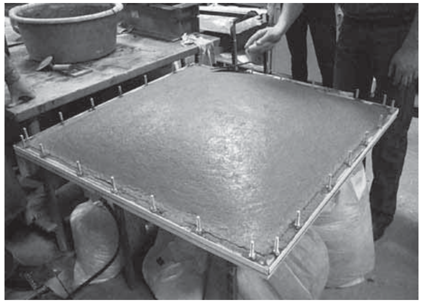
Figure 1. Short glass fiber concrete is evenly placed on the surface of rubber membrane (pneumatic mould).



THIN WALL SHELL FABRICATION METHOD

On the flat surface of non-inflated pneumatic mould was spread out and smoothed down short glass fiber-concrete mix (see Figure 1). Before concrete binding, mould is inflated by air till its final shall shape size (moderate curvature shells were elaborated (see Figure 2)). During concrete hardening air pressure in pneumatic mould is keeping constant value. After the concrete is coming hard, air in the pneumatic mould is blowing out and shell is demolding. Experimentally fabricated and investigated shells were 1m$_x$ 1m curved quadratic plates with the thickness 15mm. Simultaneously with every shell three cubes 10 x 10 x 10 cm and three prisms 10 x 10 x 40 cm were fabricated using the same fiberconcrete. Cubes were tested under compression, prisms under 4-point bending conditions.

Figure 2. Rubber mould is inflated by air till its final shell shape size was reached.

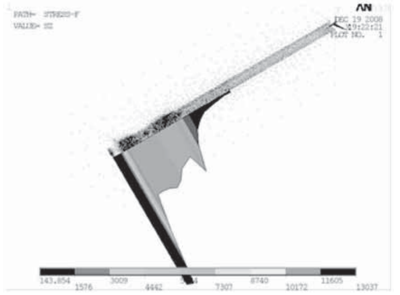


FIBERS PULL-OUT MECHANICS

Corresponding to investigation performed in [1], the pull-out process can be divided into three stages- a) fibre 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 fibre embedment is small (short fibre or pulling out the shorter end of fibre which is bridging the crack) delamination is reaching all length of fibre after that fibre with friction is pulling out. If fibre embedment is large, fibre is breaking at the length L in concrete, after what free fibre end with friction is pulling out of matrix; d) stretched fibre 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. Three numerical 2D models were investigated: 1) single glass (or carbon, or straight steel) fibre is embedded into concrete matrix with perfect bond between them and subjected to external pulling load; 2) 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. Stresses in fiber along the line parallel to fiber axis in vicinity to interface with matrix (0.95 of fiber radius) are shown in Fig. 3.

Figure 3. Shear stress profile in the concrete matrix near fiber.



Stress peaks at the front of delamination zone (corresponds to singularities in classical solution) are explaining mechanism of fiber 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 going deeper along the debonded fiber – concrete matrix interface (starting from the outer surface of concrete block) 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. Numerical model were elaborated to describe fiber end sliding motion after the break in the concrete matrix or in the case when delamination reach the embedded end of fiber. FEM model with FE contact elements between fiber and matrix were exploited. Numerically calculated force – pulled out fiber length were compared with experimentally measured and friction coefficient values between fiber and concrete matrix during fiber sliding out of matrix were obtained.

FIBERS BUNDLES PULL-OUT

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 is 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 the fibers in a composite shell and consequent core sliding out (this process is governing by friction between adjacent fibers).

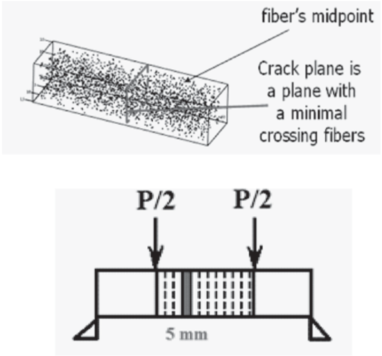
PULL-OUT EXPERIMENTS

Obtained numerical results were validated by performed experimental tests 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 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 1.5 mm. 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).

MACROMECHANICAL MODELING

The construction member cracking and post cracking behavior was investigated experimentally testing prisms (10 x 10 x 40 cm) under 4-point bending (till macro-crack mouth opening displacement (CMOD) reaches 3 mm) and obtaining applied load – CMOD diagrams. The same process was simulated numerically on the base of elaborated structural macro-crack (bridged by fibers) opening model. Elaborated model takes into account the types of fibers were used and also the quantity of each fiber type in the concrete mix. A fiberconcrete beam with chaotic reinforcing elements (fibers and fiber bundles) orientation subjected to four point bending was modeled. A random distribution function was applied to determine location and orientation angle of each reinforcing element. Monte-Carlo simulations were performed to obtain each fiber location and orientation in every particular prism. After that, weakest (critical) crossection was recognized as the crossection with the smallest amount of elements crossing it. In the critical cross-section the number, location and spatial orientation of each element was known. It's meant that orientation angle and embedded length of every element crossing the cross-section is known with respect to the plane of cross-section (Fig. 4 right picture). The crack starts to open (this procedure in the model is happened step by step increasing crack mouth opening displacement (CMOD)). At every step (known value of CMOD=δ) every element crossing the crack starts to pull out. Information about every particular fiber location orientation, type and embedment length is known previously from the simulation procedure and is keeping in the model. Then the corresponding data from the database file which contains all information from pull-out experiments with single fibers must be correctly read and applied. Load is bearing by every particular fiber is crossing the crack, denotes depending on the element location, orientation (to crack plane) and its location point opening. Summarizing all local loads we are obtaining bending moment working in the crack plane and corresponding value of external force. Performing numerical simulation of above mentioned crack opening process we are obtaining theoretical applied load- CMOD curve.

Figure 4. Fibers midpoint coordinates generated by single run of Monte-Carlo simulation. In every simulation fibers midpoint coordinates and spatial orientation angles were obtained. Crack's plane was obtained as a plane with a minimal number of fibers crossing it.



MODEL VERIFICATION

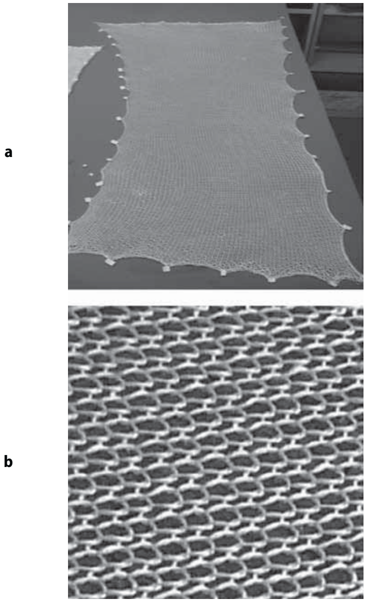
Fiberconcrete prismatic samples were elaborated. Fully computer driven testing mashine Zwick-150 (with ultimate force 150kN) were used. Stress- prism midpoint deflection diagrams for glass fiber and carbon fiber concrete were obtained. Experimentally obtained pull-out laws were used as the main input data for the proposed structural FRC fracture model 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 10x10x40 cm) 4 point bending and planar samples (10 cm x 1.5 cm x 40 cm) were tested by tension.

KNITED FABRIC FABRICATION

Interest to concrete matrix composites, reinforced by knitted fabric, have increased in recent years. Such materials are exhibiting attractive mechanical properties including high energy absorption and impact resistance. Yarns loops are arranged in structures. In woven fabric, threads traditionally are running horizontally and vertically. Contrary, in the case of knitted fabric, strands are forming loops. A knitted fabric is highly deformable in all directions. Depending on fibers are used, some of them are more deformable than others. The reason is – yarns are not making any straight line anywhere in the knitted fabric. Is easily to recognize possible motions in the fabric – threads sliding, loops twisting, bending and stretching leading to technological advantage – excellent deformability, shape forming ability and flexibility, which allows it to be used in any complex shape mould without folds.

Investigated were glass fiber weft knitted fabrics. Type E glass fiber yarns, produced by JSC "Valmieras stikla šķiedra" (Latvia), were used. Density of the glass was $\rho = 2540$ kg/m^3, diameter of the yarn d was determined and was equals 0.37×10^{-3} m. Linear density of the glass yarn was calculated and was equals to 275.6 tex. Value of elastic modulus for glass yarn was obtained from manufacturer and was 73.4 GPa. Cotton and glass yarns were used for knitted fabric preparation. Cotton knitted fabric was prepared by "Juglas manufaktūra" , glass knitted fabric was prepared by ourselves in Riga Technical University (using knitting machine Neva-5). Prepared samples of the knitted glass fiber fabrics are shown in the Fig. 5.

Figure 5. a) our made glass fiber knitted fabric sample is ready for composite reinforcement; b) fabric's structure.



On the flat surface of non-inflated pneumatic mould was spread out and smoothed down concrete with two and three glass fibre knitted fabrics (see Figure 6). Simultaneously prisms 10x10x40 cm reinforced by the same fabrics were fabricated and later experimentally tested under 4-point bending conditions (see Figure 7).

Numerical model, based on fiber bundle rupture mechanism in concrete were used to predict fiberconcrete post cracking behavior. Theoretical results were compared with the data obtained in experiments.

Figure 6. Concrete shell fabrication reinforced by three layers of knitted glass fiber fabric.

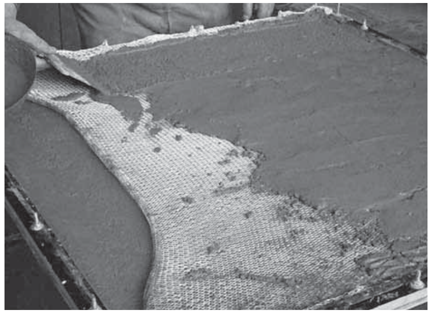


Figure 7. Concrete prisms tested by bending.

CONCLUSIONS

Numerical investigation for glass single fibre and fibre bundles pull out of concrete matrix micromechanics (detailed micro-stresses and micro forces) were performed. Results were compared with performed pull out experiments. Main fibre and bundle load bearing and rupture micro-mechanical 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. Model predictions were used in curved shells load bearing capacity prediction. Shells were fabricated and tested. Testing results were compared with theory. Shells reinforced by glass fibre knitted fabric were fabricated. Shells load bearing capacity were predicted based on strength data obtained in 4-point bending tests.

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ABSTRACT

Two differently reinforced thin glass fiber concrete matrix shells were under investigation: a) shell reinforced by uniformly distributed short glass fibers (three different fiber concentrations were observed); b) shell reinforced by welf knitted glass fiber textiles. Shells were produced using pneumatic mould technology. Simultaneously flat thin (with the same thickness as a wall of the shell) fiberconcrete samples were fabricated and tested by tension. In experiments with short fibers concrete AR glass fibers and carbon fibers were used. In the case of textile reinforcement, glass fibers were used. Detailed micromechanical investigation for single fiber and few fibers pull-out micromechanical mechanism were performed numerically (using FEM modeling) and experimentally. Fiberconcrete fracture (and post-cracking) behavior were investigated (experimentally under three and four point bending) depending on concrete matrix strength and fibers amount. Numerical model, based on fiber bundle pull-out mechanism in concrete were used to predict fiberconcrete post cracking behavior in the shell subjected to external pressure. Theoretical results were compared with the data obtained in experiments.

ABSTRAKTS

Divas dažāda veida stiegrotās čaulas tiek aplūkotas darbā: a). čaula stiegrota ar īsam stikla vai oglekļa šķiedrām (trīs dažādas šķidru koncentrācijas tika apskatītas); b).čaula stiegrota ar stikla šķiedras trikotāžas audumu. Čaulas tika izgatavotas pielietojot pneimatisko veidņu tehnoloģiju. Vienlaikus katras čaulas izgatavošanai, plakanie paraugi tika izgatavoti ar čaulai līdzīgu biezumu un stiegrojumu. Paraugi tika testēti uz stiepi. Eksperimentos ar īso šķiedru fibrobetoniem tika izmantotas AR stikla un oglekļa šķidras. Tika pētīta stikla un oglekļa šķiedru mikromehānika betonā, tāda, ka vienas šķiedras, vai šķiedru kūļa radītie spriegumu mikro-lauki un izraušanas dinamika (skaitliski modelējot ar GEM un eksperimentāli). Fibrobetonu stiprība un pēc-plīšanas mehāniskā uzvedība tika pētīta eksperimentāli pie trīs un četru punktu lieces mainot betona matricas stiprību un šķiedru daudzumu materiālā. Skaitliskais fibrobetona plīšanas modelis (modelī tika izmantots mehāniskais apraksts šķiedru kūļa izraušanai no betona) tika izmantots lai prognozētu čaulas sabrukšanas mehāniku zem pielikta ārēja spiediena. Teorētiskie rezultāti tika salīdzināti ar eksperimentāliem datiem.

АБСТРАКТ

Красников А., Лусис В., Лапса В., Залесский Е., Захаревский В., Мачановский А. Бетонные оболочки армированные стеклянными волокнами

В работе рассмотрены тонкостенные бетонные оболочки изготовленные методом надувной опалубки. Оболочки армировались двумя разными способами – а) короткими стеклянными либо угольными волокнам; б) трикотажной стеклоткаью. Одновременно с изготовлением оболочек отливались плоские образцы с одинаковой с оболочкой толщиной и армированием. Исследовалась микромеханика коротких стеклянных и угольных волокон в бетонной матрице (численно используя МКЭ и экспериментально). Исследовались микромеханика вытаскивания и поля напряжений вокруг одного волокна либо пучка волокон вытягиваемых из матрицы. Разрушение фибробетона (и поведение в процессе роста трещин) исследовалось экспериментально при 3х и 4х точечном изгибе варьируя объемное содержание волокон ипрочность бетонной матрицы. Численная модель трещинообразования, базирующаяся на микромеханике вытягивания пучка волокон из бетона, использовалась для предсказания растрескивания фибробетонных оболочек подверженных внешнему давлению. Результаты прогнозирования сравнивались с экспериментальнополученными.