Crack Opening Investigation in Fiberconcrete

Arturs Macanovskis, Vitalijs Lusis, Andrejs Krasnikovs

Abstract—This work had three stages. In the first stage was examined pull-out process for steel fiber was embedded into a concrete by one end and was pulled out of concrete under the angle to pulling out force direction. Angle was varied. On the obtained force-displacement diagrams were observed jumps. For such mechanical behavior explanation, fiber channel in concrete surface microscopical experimental investigation, using microscope KEYENCE VHX2000, was performed.

At the second stage were obtained diagrams for load- crack opening displacement for breaking homogeneously reinforced and layered fiberconcrete prisms (with dimensions 10x10x40cm) subjected to 4-point bending. After testing was analyzed main crack.

At the third stage elaborated prediction model for the fiberconcrete beam, failure under bending, using the following data: a) diagrams for fibers pulling out at different angles; b) experimental data about steel-straight fibers locations in the main crack. Experimental and theoretical (modeling) data were compared.

Keywords—Fiberconcrete, pull-out, fiber channel, layered fiberconcrete.

I. INTRODUCTION

TODAY safety of buildings and structures is playing important role in building industry. Fiberconcrete was invented approximately one hundred years ago, but it gained its popularity in recent years thanks to its durability, as well as the feature of its internal structure (on the macro and micro level) and that is why fiberconcrete is more and more often used in construction. It is known that all the rest types of cement concrete without fibers have high results regarding compression, but when bent, they bear low loads if speaking about resistance to tension and cracks. This is why fiberconcrete gradually presses back the classic concrete from the construction industry [1]-[10]. Fiberconcrete exceeds the classic concrete by duration of exploitation by 15-20. Fiberconcrete got its name thanks to its reinforced components, for example, steel fiberconcrete, glass fiberconcrete and other. Durability of composite material directly depends on the features of components contained in it, if we select the right components, we can reach a high level of composite quality. Different type of fibers are used in fiberconcrete as the components (steel, polymeric, glass and other), which grants the concrete various types of features. But one of the most important features of fiberconcrete is the resistance to deflection that is why different types of steel fibers are used. More and more scientists show interest about the way of improving durability, as well as increasing the fragility of fiberconcrete to reach the optimal concrete quality. As it was known, not long ago one integral metal reinforcement along the center of concrete structure was used, which failed to give the desired results regarding resistance to cracks and fragility. Likewise integral reinforcement made the concrete structure heavier and the procedure of assembly was more difficult. Use of integral reinforcement, from the point of view of the economics, is expensive and irrational. Thanks to the fibers the structures have become lighter and cheaper. The producing enterprises can cheaply produce things with high exploitation features. This is exactly why the scientists began to study different methods of fiber introduction, as well as their orientation by their volume in the concrete matrix. Standard method of chaotic fiber distribution by the volume was pushed to the sidelines. Layered fiberconcrete have appeared, where each reinforced layer bears its working force (for instance: when bending the sample, the lower layers of concrete are reinforced, and the upper layers are not reinforced, because they bear no bending load).

II. EXPERIMENTAL INVESTIGATION

A. Fiber's Micromechanics

Samples were produced that contained straight steel fibers 26mm long and with a diameter of ≈ 0.5mm.

Fig. 1 Surface scanning at 40°

The samples were tested for fiber pull-out and studied using a scanning measuring microscope KEYENCE VHX 2000 [13] (see Fig. 1) with a digital computed video camera and image processing software. This microscope allows receiving 2D and 3D images.

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A. Krasnikovs Dr.Sc.Ing., professor, Institute of Mechanical Engineering and Concrete Mechanics Laboratory(www.bml.rtu.lv), Riga Technical University, Ezermalas Str.6k Riga, LV 1006 Latvia (e-mail:akrasn@latnet.lv).

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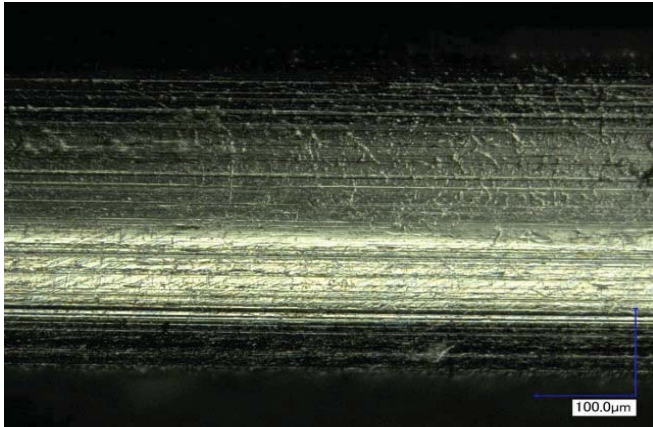Vol:8, No:4, 2014

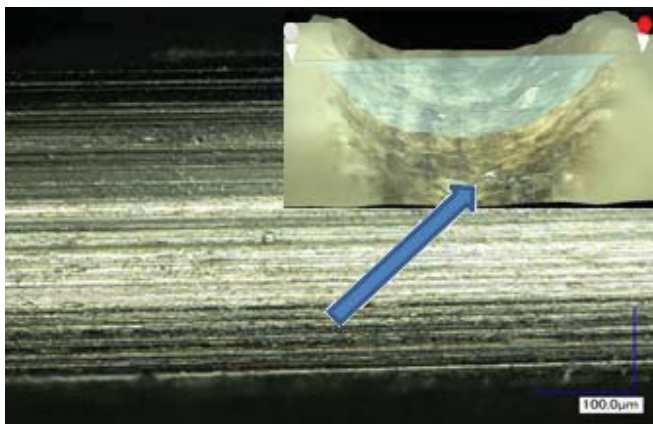Fig. 2 SSF surface before pull-out

Fig. 3 SSF surface after pull-out

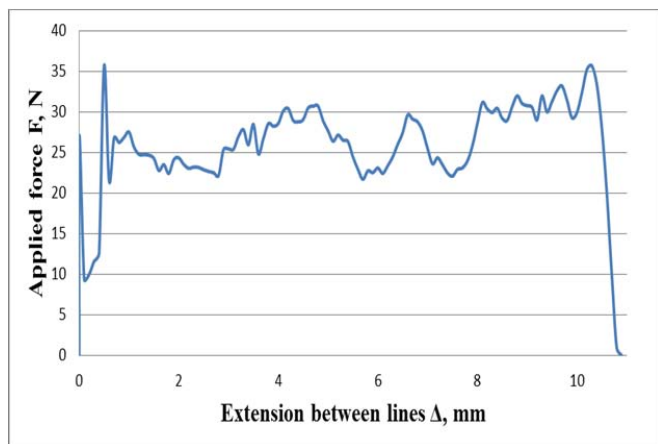The diagram of pull-out of straight steel fiber at an angle of 80° is represented on Fig. 4.

Fig. 4 Extension of straight steel fiber orientated at an inclination of 80°

Analysis of fiber's surface showed that the SSF, before pull-out (see Fig. 2) presents on the fiber's surface along the whole length clear deepened strips (roughness), as well as relief crackling in a form of small cracks. The surface after SSF (straight steel fiber) pull-out (see Fig. 3) is more worn-through and the strips are already worn-through by the surface of concrete. The fiber was exposed to friction. Fig. 3 shows the canal (trace) left by the fiber after pull-out and we see traces of steel (glossy spots) along the channel's surface, where the fiber was exposed to friction, as well as stretching strips along the length of all tested channel [5].

During microscopic study of the sample's surface (see Fig. 5), we see a trace of pull-out fiber of the concrete matrix. The trace looks like an even, undamaged surface, which means that the fiber, during the initial charge, destroys the concrete surface in the area of fiber output (see Fig. 6) and there is no fiber friction (this is proved by broken-off particles during the experiment).
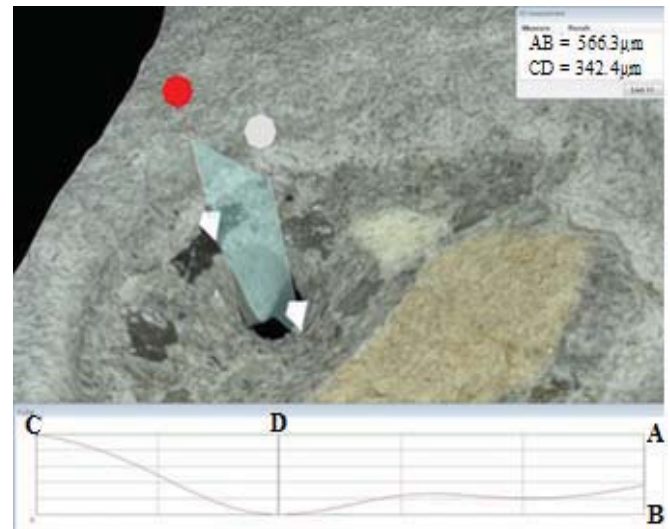

Fig. 5 Analysis of canal surface in the sample N38 (3D)

The channel surface is wavy (see Fig. 5) and it is known that the fiber in this sample was orientated at an angle of inclination 80°. Thanks to this angle it is possible to define the length of trace (canal) left by the fiber after concrete destruction. Fig. 5 shows a section, in which the depth is represented (AB = 566.3μm) and the length (CD = 342.4μm) (see Fig. 6). Still, in this case the CD length is not the length of trace left by the fiber after concrete destruction. To calculate the length of trace, the sinus function was applied (refer to (1)) for the inclination angle (See Fig. 7).

$$\sin(90° - \alpha) = \frac{CD}{CB} \qquad (1)$$

where α – fiber angle, °;

CD – length obtained during experiments, μm;

CB – canal length left by the fiber when matrix is broken, μm.

Hence a formula (2) arises:

$$CB = \frac{CD}{\sin(90° - \alpha)} \qquad (2)$$

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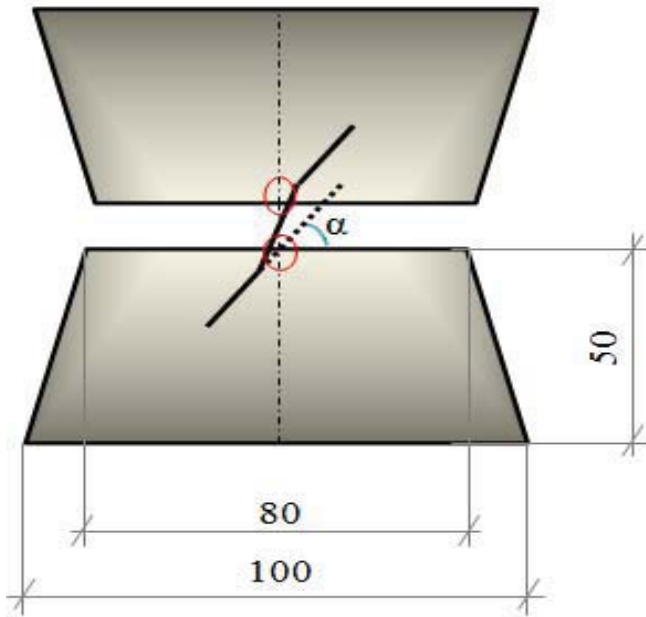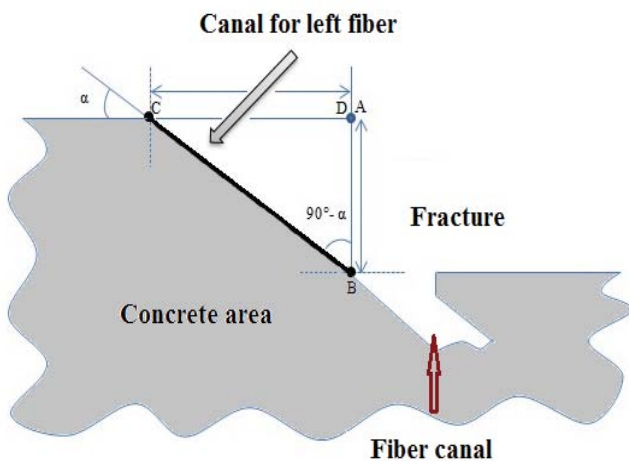Vol:8, No:4, 2014

Fig. 6 Areas of concrete spalling

Fig. 7 Canal surface when spalling the concrete and turning the fiber

The point C in Fig. 5 is located higher than the studied length of trace ≈ by 40% (diagram of Fig. 5). Hence CD = 342.4*(100%-40%) = 342.4*0.6=205.44μm or 0.205mm. We find CB (refer to (2)): CB = 0.205 / sin (90°-80°) = 0.205/sin (10°) = 0.205/0.1736=1.18mm. As the point D has been taken from the very beginning of the canal, the found distance 1.18mm includes the diameter of the pull-out fiber and the length of the searched canal at concrete breaking. It is required from 1.18 – (0.5) - 0.1 = 0.63mm – the true length left by the fiber after destruction of matrix. 0.1mm – distance parting the fiber from the length of trace is left when the concrete matrix is damaged.

The Part 2 (see Fig. 9) of the surface of sample N38 no formation of channel length was observed (the trace that has been left is seen because the steel fiber was bent manually to get the picture of surface under a microscope). The graph (see

Fig. 4) shows an intense decrease of the applied force to ≈0.5 ÷ 0.6mm, which matches the found distance CB = 0.63mm. Conclusion: the initial decrease is explained by the destruction of matrix of the sample tested by fiber. After matrix destruction the fiber has intense delaminating and pull-out of fiber of the concrete matrix by friction.

Fig. 8 Studied surface of the first part of sample N38

Fig. 10 shows the studied surface; where the fiber takes the maximum, intense surface deterioration when pull-out the fiber of the concrete matrix. It should be noted:
a) surface is rugged with cavern formation;
b) the surface has visible particles, which leads to friction and accumulation, and when pull-out the fiber to congestions. The diagram in Fig. 4 – with the length of 5.7mm and 7.3mm of the pull-out fiber we see the decline of force cased by congestions.
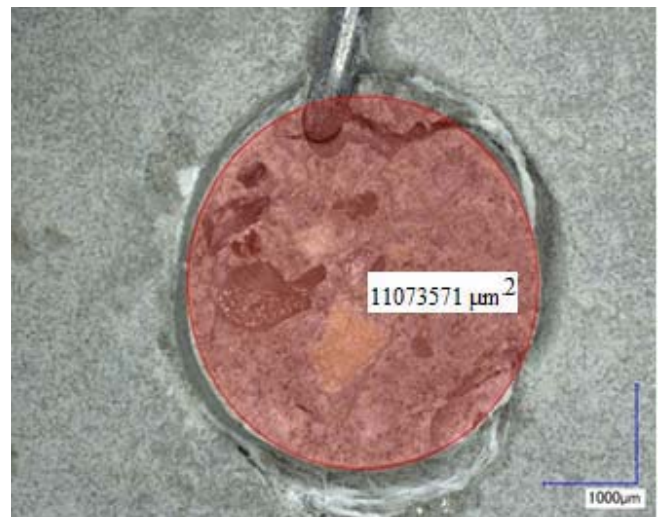

Fig. 9 Studied surface of the second part of sample N38

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Fig. 10 Canal surface left by the orientated fiber at an angle of 80°

Conclusion: that each obtained sample is unique in its own way and the obtained diagrams of dependence (the applied force from the length of the pull-out fiber) are explained in the micro environment individually. It is seen that with decrease of the inclination angle of the fiber the length of trace of the broken concrete increases. When decreasing the inclination angle of fiber, the effect of fracture of surface of two sample's parts is increased. It is difficult to foresee what the diagram would be depending on the force application from the length of the pull-out fiber, because very many factors influence the pull-out of one studied fiber (particles, caverns on the sample surface, fracture of concrete matrix depending on the strength of concrete, bulges, and cavities). This all impacts the sample testing with dimensions 10x10x40cm at 4-point bending [1], [6].
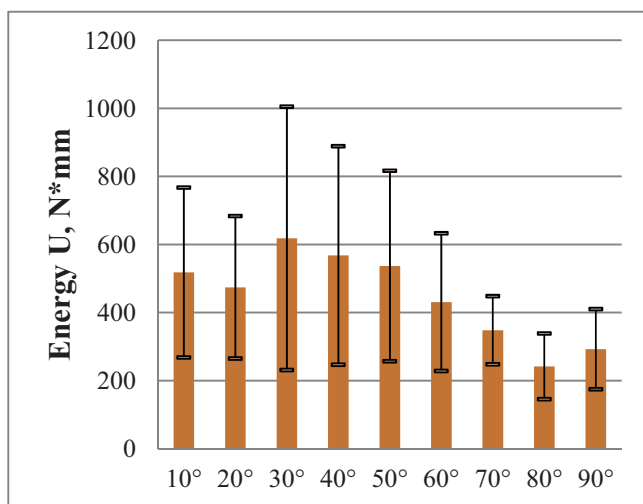

Fig. 11 Average energy of pull-out of one SSF at different angles inclination

The most energy was spent (see Fig. 11) for pull-out of the concrete at angles within this range 30°-60°. It is explained by the fact that the tested fiber bears the most friction power, as the angles are located closer to 45° (when the fiber surmounts the maximum friction) and there is plastic deformation.

At the angles of 70°-90°, the energy is minimal, because there is no plastic deformation of fiber. At these angles, there is the least surface deterioration (fiber surmounts pull-out easy, if comparing to other tested angles of the fibers). At the angles of 10°-20°, the energy accumulation takes place at the expense of intense surmount of concrete matrix breaking in the area of fiber pull-out. We shall note that none of the tested fibers was torn when was pulled out.
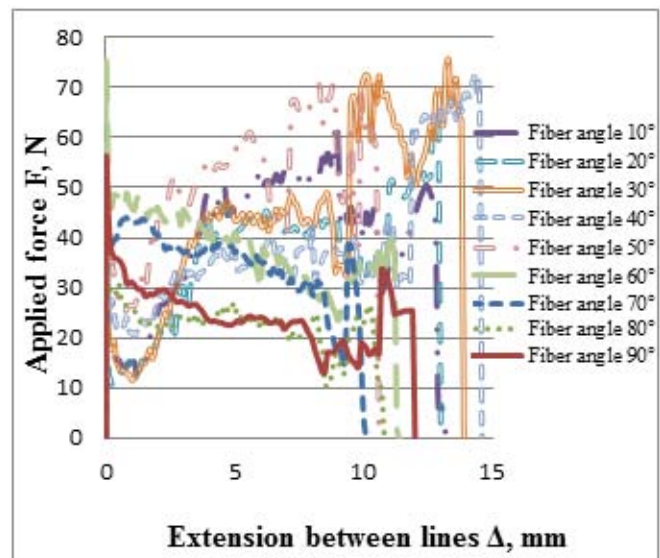

Fig. 12 Average value of pull-out of one SSF of the concrete matrix at different angles inclination

In Fig. 12 are shown pull-out diagrams for fibers embedded at different angles to pulling out force direction. The length, at which the pull-out fiber bears the load at the angles of 50°-90° = ≈ 10÷12mm, and for samples at the angles of 10°-40° is: length = ≈13–14.7mm, and it is by 8% ÷ 32% higher than at the angles of 50°-90°.

B. Fiber Macromechanics

The obtained three-layer fiberconcrete was produced according to the technology described in the Latvian patent "Technological process and device for production of fiberconcrete non-homogeneous structural elements" [11], [12]. The three-layer fiberconcrete with SSF that is 26mmlong and has diameter of 0.5mm (see Fig. 13) was reinforced in the bottom layer by 25mm and 25mm in the top layer with the fiber concentration 30 kg/m^3 and 60 kg/m^3, where

1) the bottom layer had 40g of fibers, the top layer had 80g of fibers with 30kg/m^3;
2) the bottom layer had 80g of fibers, the top layer had 160g of fibers with 60kg/m^3.

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Fig. 13 Three-layer fiberconcrete (layers with fibers on the top and at the bottom)

The three-layer fiberconcrete with SSF that is 26mm long and has the diameter of 0.5mm (see Fig. 14) was reinforced at the bottom layer by 25mm and the following layer by 25mm with the fiber concentration 30 kg/m^3 and 60 kg/m^3, where
1) the bottom and the top layers have 60g of fibers each with concentration 30kg/m^3;
2) the bottom and the top layers have 120g of fibers each with concentration 60kg/m^3.
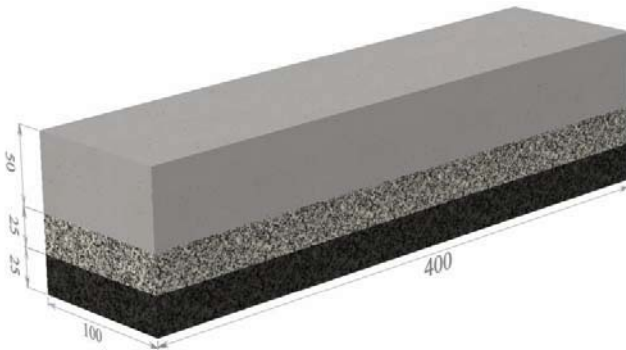

Fig. 14 Three-layer fiberconcrete (layers with fibers at the bottom)

36 samples were tested for four-point bending with SSF that are 26mm long and have diameter of 0.5mm. Figs. 15, 16 show the curves of average values of bending of the middle of prism depending on the applied bending force (every curve was obtained by averaging of data by 6 samples with each concentration of fibers per 1m^3).

It arises from the diagrams (see Fig. 15) that with small concentration of fibers the fiberconcrete with homogeneous distribution of fibers (fibers are located chaotically along the volume) bears both the least peak load, comparing to the layered samples (fibers are located only in the specific layer of concrete), and shows the least bearing capacity along all opening of main crack. It arises that during formation of fiberconcrete in layers, we can reach large bending strength. A conclusion is ready of comparison of average values of the obtained layered fiberconcrete (see Fig. 15): selection of location of the layer level influences the bearing capacity, i.e., for layered samples 50x25x25mm the obtained average value for deflection is higher than for 25x50x25mm.
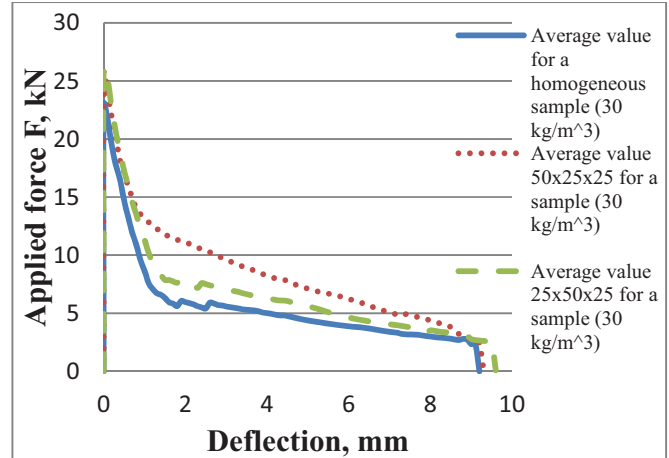

Fig. 15 Curves of average values of bending of the middle of prism depending on the applied bending load of homogeneous and layered fiberconcrete with the total (per whole sample) concentration of fibers 30kg/m^3

According to Fig. 17, the average energy for samples 50x25x25mm reaches ≈78kN*mm, and for the sample 25x50x25mm ≈63kN*mm, which is by ≈19% less than comparing to the samples having configuration of 50x25x25 mm. It is important also to know, at which exploitation loads it is planned to use plates or beams, which model the tested sample data. In case of one-sided deflection it is obvious that reinforcement of the lower sample layer leads to large increase of the bearing capacity than reinforcement of the lower and the upper layer simultaneously. The upper layer, during deflection, is subject to compressing load and partially the tensile load (neutral line goes through the layer), thereby its contribution to the beam's bearing capacity is limited, because the tensile load prevails in the lower layer [3], and the concentration of fibers in it is small. The average obtained energy for deflection for homogeneous fiberconcrete is equal to ≈51kN*mm, which is by ≈19% less than for orientated layered fiberconcrete 25x50x25mm, and by ≈35% less than for layered fiberconcrete 50x25x25mm.
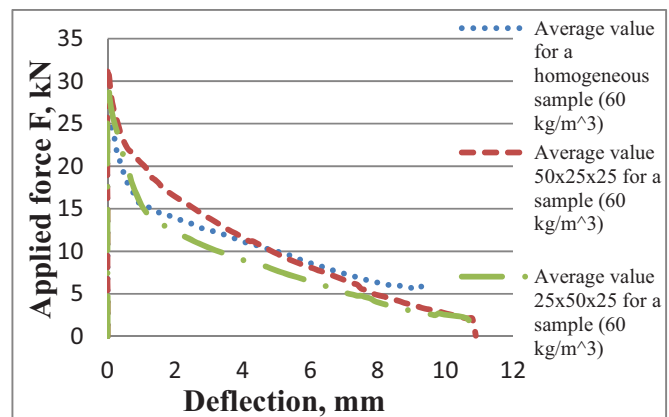

Fig. 16 Curves of average values of deflection of the middle of prism depending on the applied bending load of homogeneous and layered fiberconcrete with the total (per whole sample) concentration of fibers 60kg/m^3

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Fig. 16, by increase of concentration of fibers the averaged curves behave differently. Prisms of homogeneous fiberconcrete at deflection, when increasing the concentration of fibers by m³, managed to bear the least load with the maximum crack ≈1mm. After reaching the crack opening of 1 mm, the value of the required applied force grows, if comparing to the layered samples 25x50x25mm, which is caused by the fact that in the homogeneous samples, during the procedure of bearing the external load, the fibers connect, which are located higher and higher along the beam section.

This phenomenon proves again that the upper layer at deflection takes les part in the bearing capacity (does not work for pull-out) of the beam [2]. Comparing homogeneous and layered beams, it is clear that homogeneous fiberconcrete bears less deflection force to the beam deflection that is equal to ≈4.6mm, after this, it has higher bearing capacity to 9.5mm.
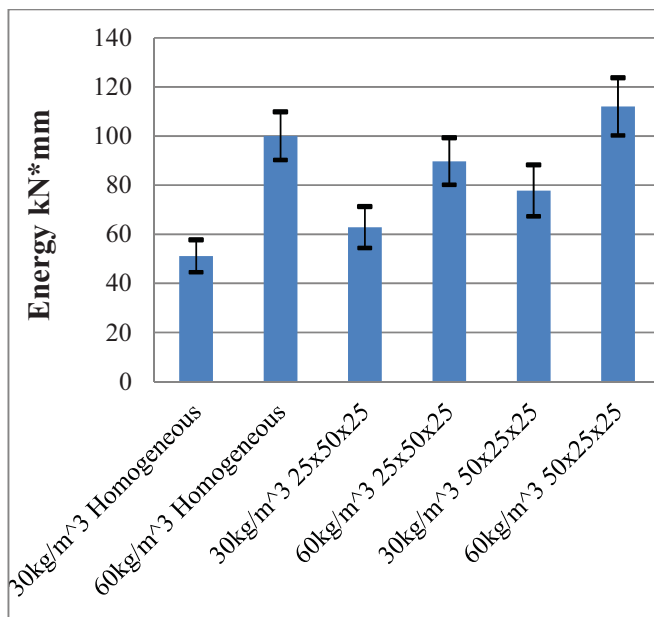

Fig. 17 Average value of spent deflection energy with SSF that are 26mm long and have diameter of 0.5mm

With the following increase of concentration of fibers per m³a moment comes when the fiberconcrete layers will have that much fiber that the load-bearing mechanism in the section by pull-out individual fibers will start changing to the load-bearing mechanism in the section by pull-out concrete fiber blocks, which might lead to reverse action: layered fiberconcrete will bear the least applied force. It is clear from Fig. 17, that the average energy for homogeneous fiberconcrete with concentration of fibers 60kg/m³ ≈100 kN*mm, and for the layered 25x50x25mm with concentration 60kg/m³ ≈90kN*mm, which is by 10% less than for the homogeneous. Energy of layered fiberconcrete 50x25x25mm with 60kg/m³ ≈112kN*mm, it is by ≈20% more than for 25x50x25mm and by ≈11% - than for the homogeneous [8].

III. NUMERICAL MODELING

The experimental and theoretical data [7] of layered fiberconcrete have been considered in diagrams Figs. 18–21, with concentration of SSF 30kg/m³ and 60kg/m³.
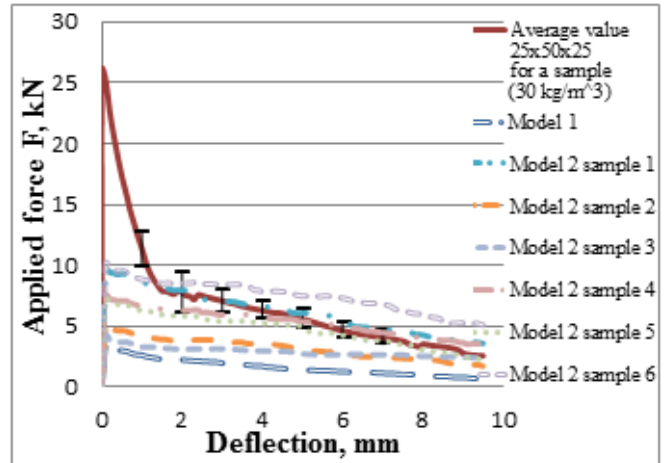

Fig. 18 Averaged curves "force – vertical deflection for layered fiberconcrete with SSF concentration 30kg/m³ after testing for 4-point bending and modeling

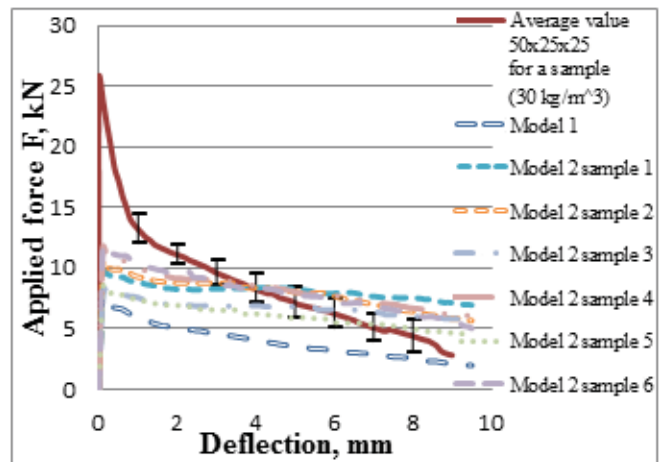
Fig. 19 Averaged curves "force – vertical deflection for layered fiberconcrete with SSF concentration 30kg/m³ after testing for 4-point bending and modeling

Model 1 shows on the images the least anticipated bearing capacity of fiberconcrete, if comparing to the model 2. Comparing with experimental data of the model 1, we can see that there is only approximation to the experimental data along all crack opening. This is caused by the fact that in the model 1 the bearing capacity of pull-out fibers located perpendicularly to the crack's surface is smaller (at 90°) than for the fibers located at the angles from 10 to 50°. The prediction of the model using a hypothesis that all fibers in the crack's section are perpendicular to its banks gives much lower bearing capacity, see value Model 1.
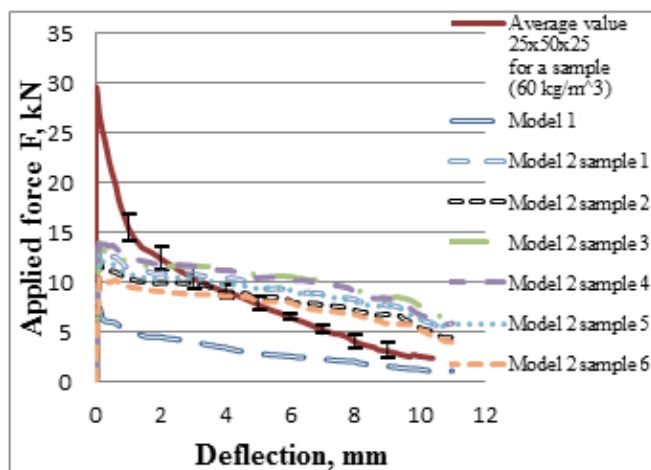
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Fig. 20 Averaged curves "force – vertical deflection for layered fiberconcrete with SSF concentration 60kg/m^3 after testing for 4-point bending and modeling
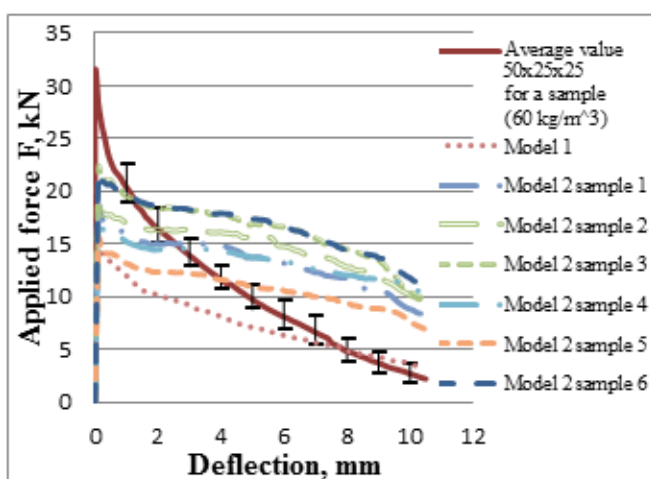

Fig. 21 Averaged curves "force – vertical deflection for layered fiberconcrete with SSF concentration 60kg/m^3 after testing for 4-point bending and modeling

Model 2 describes the fiber behavior in the crack taking the inclination angle (α), fiber height (y), as well as length of pull-out fiber (c), into account. Model 2 and experimental data are closer to each other than the model 1. This is connected with the fact that the experimentally received data of fiber orientation in the main crack approach the real (true) data. Conclusion: with the help of models 1 and 2 we can predict the bearing capacity the straight steel fibers, 26mm long and with diameter of 0.5mm, will have at the deflection from ≈1.5mm (depending on the fiber concentration). To maximally approach the experimental (true) data, it is required to analyze the performance of mechanisms not included in the models (work for crack opening in concrete, work for fiber loading at the initial stage of crack opening, work for fiber pull-out (in the model, it is partially taken into account, the behavior of fibers, which were pull-out from the concrete at the length that was bigger than a half of the fiber itself, is not taken into account)).

IV. CONCLUSIONS

1. It has been shown that as a result of fiber pull-out from the concrete matrix we observe erosion on the canal surface of the fiber in the concrete, which leads to large spread of force values for fiber pull-out at large inclination angles.
2. Analysis of the crack surface has been performed. The coordinates of each fiber have been found on the crack's surface and the diagrams have been built for arrangement of lengths of pulled-out fiber ends and angles to the crack surface.
3. The results of experiments have been used in modeling of beam behavior under load in the mode of the main crack opening.
4. Two numerical models that model the bearing capacity of the beam at the stage of the main crack opening have been developed. Good compliance of experimental and theoretical data at the stage of large openings of the crack has been received.

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[12] http://www.lrpv.gov.lv/sites/default/files/media/vestnesis/20101220.pdf
[13] http://www.keyence.co.uk/products/microscope/microscope /vhx2000/ vhx2000_ specifications_1.php

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V.Lusis is an author and co-author of 20 scientific publications, 9 patents for invention. Since 2011 he is member of Latvian Concrete Association and Latvian Materials Research Society.

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