MICROMECHANICAL INVESTIGATION OF STEEL FIBER REINFORCED HIGH-PERFORMANCE CONCRETE POST-CRACKING BEHAVIOR

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Abstract

During the fracture process of steel fiber reinforced high-performance (SFRHPC) concrete fibres are bridging the crack in the matrix providing resistance to crack propagation. Broad experimental program were realized and pull-out force versus pull-out fiber length were obtained for three types steel fibers embedded into concrete at different depth and under different angle. Follows types of steel fibers have been used– straight fibers, fibers with end hooks (Dramix), and corrugated form fibers (Tabix). Structural SFRHPC fracture model was created; material fracture process was modeled, based on single fibre pull-out law, which was determined experimentally. Elaborated model allows us to predict steel fiber reinforced concrete (SFRC) mechanical non-linear behaviour, depending on fibre content, concrete matrix mechanical properties and fibres geometry. Prediction results were validated by notched 15x15x60cm prisms 4 point bending tests.

Keywords: Steel fibres; concrete; micromechanics.

1 Introduction

Concrete is brittle. Adding short steel fibers we can increase the material stiffness, flexural and tensile strength, impact resistance, as well as obtain a quasi ductile behavior for cracked material. The use of steel fibers in concrete instead of traditional reinforcement is beneficial mostly due to simpler casting procedure. At the same time, technologically a large content of steel fibers in the concrete mix is negatively affects the mix workability. Therefore for the aim of good workability of the mix, steel fibers are limited both by their maximal content, geometry (chemical bond between steel fiber and concrete matrix is week and fibers are anchoring in the matrix mainly geometrically and by frictional forces) and length. In traditionally reinforced concrete structures the post cracking behavior is based on the steel bars tensile strength mechanism, contrary in SFRC it is the pull-out mechanism of steel fibers that determines the load bearing capacity of the cracked material. Therefore it is important to perform a detailed micro-mechanical investigation of fiber pull-out process in order to understand and characterize the behavior and crack propagation in SFRC and SFRHPC structural elements. Based on micromechanical investigations, structural SFRC fracture model will allow predict fracture and post-cracking behaviour for SFRC construction members, depending on fibers type, amount and concrete matrix properties.

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2 Steel fiber pull-out micro-mechanics

Single fiber-concrete samples were prepared in molding forms as depicted in Fig. 1. A plastic separator was inserted to ensure that the applied force is transferred through the fiber thus causing pull-out. The mechanical investigations of pull-out mechanisms for three types of steel fibers: straight steel fibers, Dramix fibers (with end hooks) and Tabix fibers - corrugated with round cross section shape, were executed; as a result pull-out laws (pull-load vs. pull-out displacement) were obtained. Fiber length for all types was 50 mm. Steel fibers with round cross-section were used with the diameter of fibers 0,8 mm, 0,75 mm and 1,0 mm for straight, Dramix and Tabix fibers respectively.

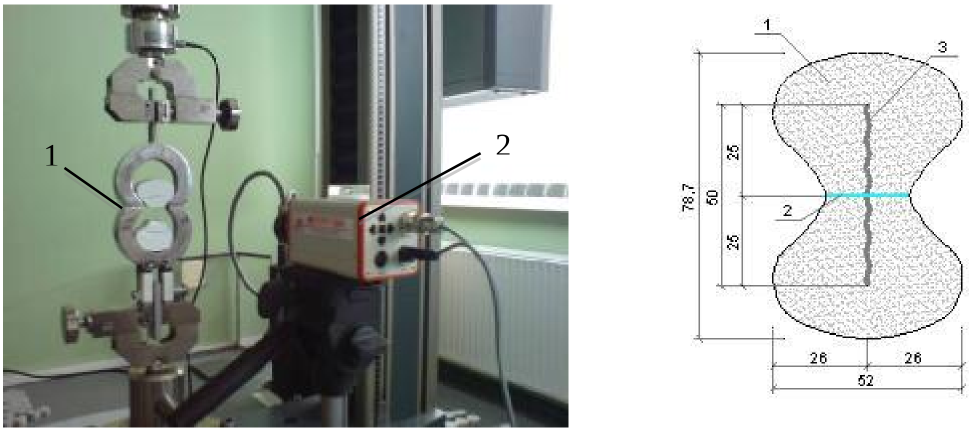

Fig.1 Fiber pull-out experimental set-up: 1-testing grips, 2-videoextensometer (Left picture); concrete sample with embedded fibre 1-concrete matrix, 2-plastic separator; 3-steel fiber.

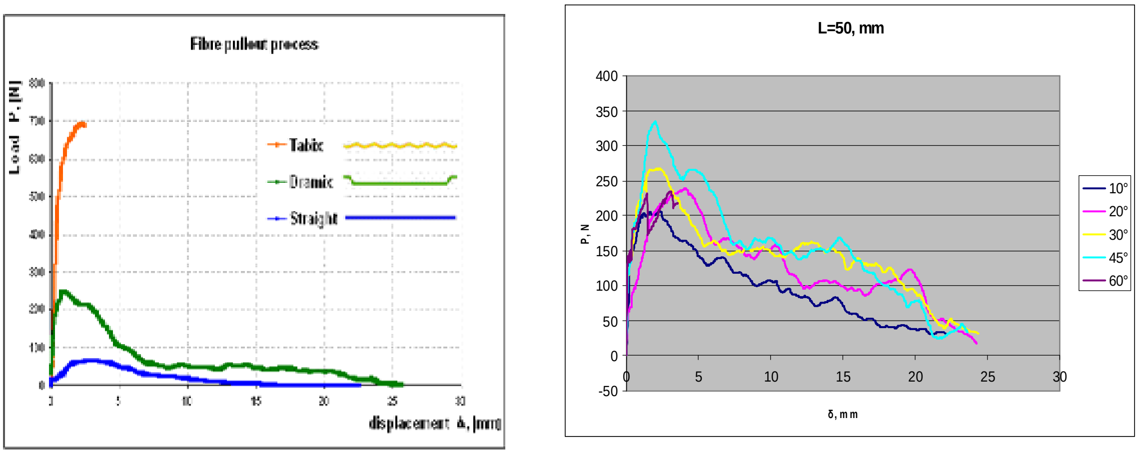

Fig.2. Pull-out low for different form fibers embedded at 25 mm having $a = 0^o$ (left picture); Dramix fibers (embedded at 25 mm) pull-out lows depending on $a = 0^o$; 10^o; 20^o; 30^o; 45^o; 60^o.

In the framework of present experimental investigation for each type of fiber, five different embedded lengths have been observed in the investigation – 25 mm (symmetrical embedding of 50 mm long fiber), 20 mm, 15 mm, 10 mm and 5 mm. The embedded lengths can also be noted in normalized form with the respect to the total fiber length L thus obtaining 0,5·L, 0,4·L, 0,3·L, 0,2·L and 0,1·L long embedded lengths. For each embedded length six different fiber orientations (measured by angle a to pull-out direction) were investigated: a = 0°; 10°; 20°; 30°; 45°; 60°. For each configuration of fiber matrix alignment a total number of 9 samples were produced thus ensuring adequate statistics of the performed tests.

Simultaneously micro-stress and loads pictures around the fibers were investigated numerically by FEM.

3 Fracture macro-mechanics

3.1 Macro-crack growth model

Experimentally obtained pull-out laws were used as the main input data for the proposed model with the goal to predict linear and non-linear behavior of SFRC notched beams under bending loads. Some preliminary attempts were done in [1]. Increasing the load is applied to the beam the cracking process is starting. Micro cracks are growing and linking forming large cracks till the moment then one or more macro crack (in our case crack was started from the notch) is crossing whole tensioned part of the beam crossection. After the formation of the crack the tensile load is still transferred through the crack by the fibers (the bridging effect). Because the fibers are being pulled out of the concrete matrix the ability of the SFRC beam to carry the applied load in the post-cracking state purely depends on the capacity of fibers in broken crossection to carry pull-out loads. At the same moment number of fibers crossing the crack surface is depending on fibre volume fraction in the material. According to the pull-out curves, were obtained, it follows that only for very small values of d fibre resistance is increasing (especially for straight and Dramix fibers), and after reaching the maximal value (see. Fig.2.), fibre resistance to withstand pull-out loads starts to decrease and thus decreases the load bearing capacity of the whole beam's broken crossection.

In the model the behavior of SFRC beam was simulated by calculating internally existing load bearing value of each fiber crossing the crack (using this fibre experimentally measured pull-out curve), depending on crack opening value b_i at the location of this

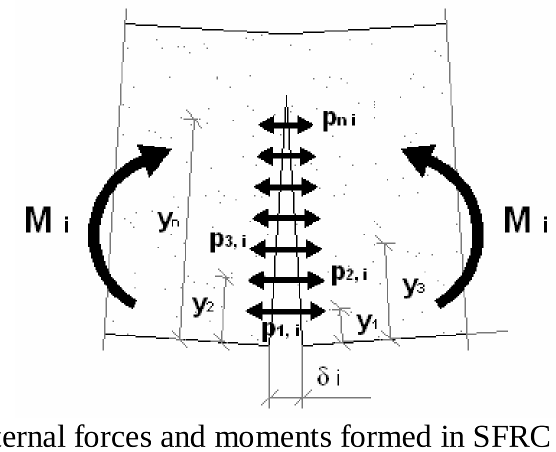

Fig. 3. Scheme of internal forces and moments formed in SFRC beam at post-cracking stage.

particular fiber (see Fig.3.). Experimental observations shown that the total crack height is approximately constant regardless of size of the crack opening d_i (when $d_i \in (0, 5mm)$). At the same moment macro crack is reaching crack opening value 5mm is unstable. In average, the crack surfaces have been assumed as a plane, therefore the local crack opening b_i can be simply geometrically determined from corresponding maximal crack opening d_i. The iteration procedure of beam behavior modeling in bending was performed according to step sequence, with the maximal crack opening d_i values within the range from 0 to 6 mm.

At each step "i" with the corresponding maximal crack opening d_i, firstly the local crack opening b_i is calculated as a function of distance y_n:

$$b_i = f(y_n) \qquad (1)$$

As the local crack opening b_i is known at each distance y_n, the force p_i transferred through the crack can be calculated using previously obtained fibre pull-out laws. Force p_i depends on number of fibers in concrete (fibre volume fraction V_f), particular fibre embedded length and orientation angle to the crack's surface. The volume fraction V_f of each fibre type could be easily determined from corresponding fibre weight fraction W_f. Further, number of each type of fibers on one crack's surface unit was determined, as the average fibre amount crossing the crack plane with chaotic fibers orientation and chaotic embedded length distributions (were performed Monte-Carlo simulations and modeling results were compared with performed direct experimental measurements). The influence of fibre type, fraction and orientation actually can be summarized within one coefficient, which in this case is defined as fibre factor k_f. With the goal to incorporate into model unexpected fracture phenomena (synergetic fiber bridging effects) fitting coefficient k were introduced multiplying fiber factor kk_f. Once obtained k value from model prediction comparison with one experimental curve, all another curves will be predicted (depending on fiber amount and "fibercocktail "structure). Now the internal force transferred through the crack's surface unit can be calculated. From the pull-out curves the force $p_{n,i}$ corresponding to a particular crack opening b_i can be determined all along the crack height as schematically depicted at Fig.3. From the calculated values of internal forces $p_{n,i}$, resulting bending moment M_i and corresponding external force P_i can be determined corresponding to each crack opening value d_i. Relation of externally applied load P as a function of crack opening displacement d is thus obtained at each step. The force P represents total force applied to the beam that is divided in two symmetrical forces. To run the algorithms of the model, computer software was elaborated.

3.2 Prisms under 4-point bending. Experimental investigation

SFRC and SFRHPC beams with dimension 15x15x60 cm were cutted by diamond saw at the depth of 1 cm forming the notch on the bottom side of each beam. The span length between underneath beam supports was L_S=50 cm and the distance between symmetrically applied loads L_P=15cm. Central upper midpoint deflection as well crack mouth opening displacement (CMOD) were measured electronically.

4 Post cracking prediction and results analysis

The proposed model was applied for SFRC and SFRHPC behavior prediction for materials with various fibre types and concentrations. SFRC mixes with fibre concentration within the range from 50 kg/m^3 to 400 kg/m^3 and still high workability were studied. At Fig. 4 are shown model prediction comparison with experiment for SFRC having one king of fibers –Tabix, as well as for SFRC with “fibercocktail” (see table 1).

Table 1.

Nr.	Mix name	Fibre type and amount in kg/m^3					Total amount of fibres in kg/m^3
		Tabix 60, d=1,0	Tabix 50, d=1,0	Dramix 30, d=0,54	Straight 13, d=0,16	Straight 6, d=0,16	
1.	F56	-	127	34	24	10	195
2.	F68	184	-	-	-	-	184

Nr.	Mix name	Amount of the ingredients in kg/m^3					Density kg/m^3
		Cement	Microsilica	Aggregate	Water	Plasticizer (% of cem)	
1.	F56	565	25	1381	224	1,63	2400
2.	F68	596	52	1326	210	1,66	2420

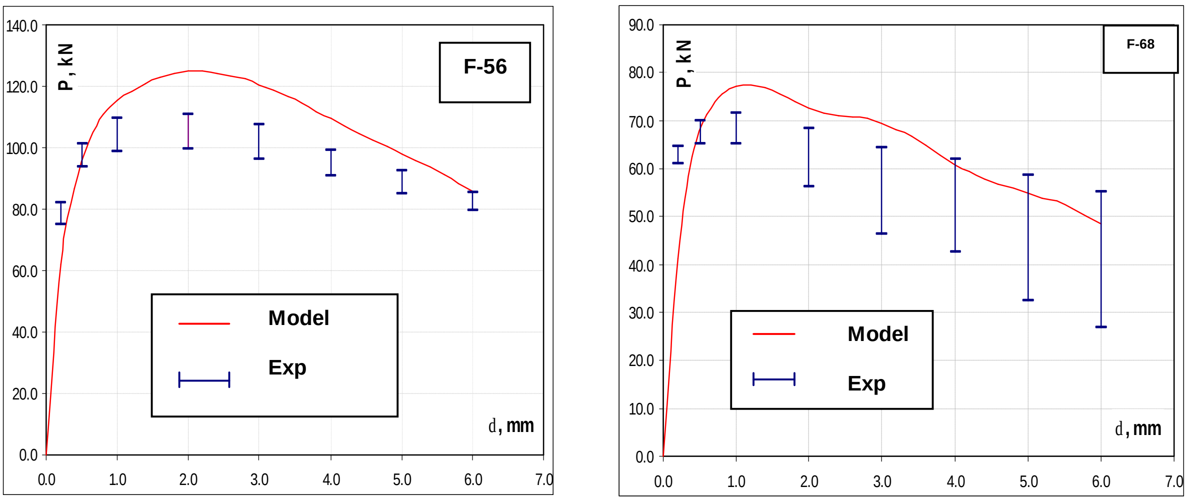

Fig. 4. SFRC prisms post-cracking behavior under 4 point bending. Mix F56 (left picture); mix F68 (right picture).

Comparison with experiments shown: model succeeded to agree with the experimental results regardless of the diversity of fibers were observed. Interpretation of these results can be based on experimental detailed data for fiber pull-out, were used in the model, as the main micro-mechanical mechanism of non-linear SFRC and SFRHPC post-cracking behavior. Good modeling and experimental results agreement allows us to be certain predicting post cracking behavior of SFRC with different fiber content and type's combination. The validity of the proposed model has been experimentally proved for SFRC beams with fibre concentrations up to 400 kg/m^3.

At Fig. 5. are shown stress-deflection curves for SFRC having different concentrations of Tabix 50mm long (d=1mm) fibers in concrete matrix F68.

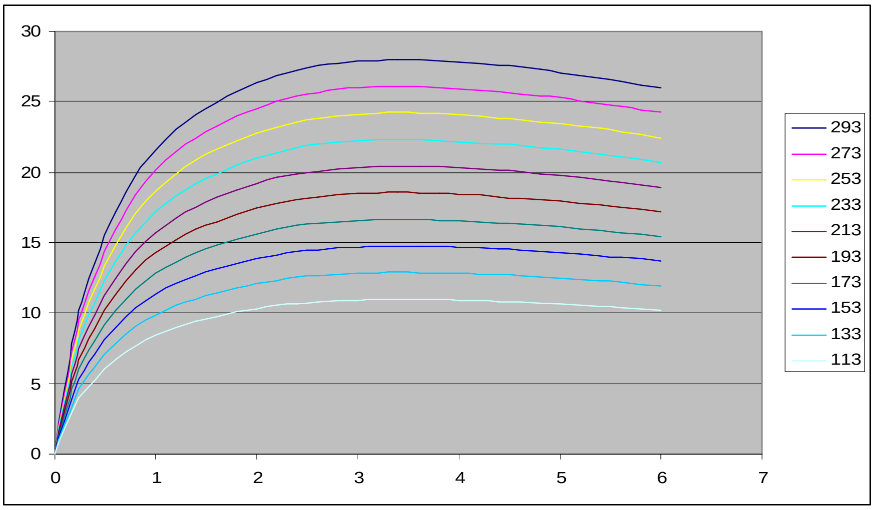

Fig. 5. Predicted stress-deflection curves for SFRC containing different amount (from 113kg.m^3 to 293kg/m^3) of one type of steel fibers (Tabix l=50mm, d=1mm) (Beam crossection size is 15x15cm). CMOD (mm) –horizontal axes; Applied stress –verticals axes.

5 Conclusions

Good agreement with the experimental results confirms that the main non-linear micro-mechanisms have been successfully comprehended and applied in the proposed model. The proposed beam behaviour prediction model proved to be valid despite the rather simple approach and assumptions. The validity of the proposed model has been proved for SFRC and SFRHPC beams with fibre concentrations up to 400 kg/m^3

References

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