MODELING OF FIBER BRIDGING BEHAVIOUR IN SFRC

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ABSTRACT

By adding fibers to concrete mix the objective is to bridge discrete cracks providing for some control to the fracture process and increase the fracture energy. Fibers become active mainly when cracking starts and deformation of the fiber occurs. The pulley approach by Aveston and Kelly can be used to describe the bridging phenomena of a fiber crossing a cracked surface, where the bond-slip of the fiber is equal to the crack opening displacement. As the fiber is able to damage a part of the matrix, the bridging phenomena of a fiber crossing a cracked surface could be described by using the pulley that is attached to the matrix via a spring. In the modified model the crack opening is greater than the fiber slip. The displacement for which the fiber becomes effectively involved in the tension carrying mechanism is effective length which depends on the material parameters obtained from fiber pullout tests for varying angle and fiber types.

Keywords: effective crack width, fiber displacement, orientation angle, pullout test

INTRODUCTION

The low tensile strength of concrete is due to the propagation of internal micro cracks. The tensile strength of concrete could be improved by suitably arranged and closely spaced wire reinforcement. By adding fibers to concrete mix the objective is to bridge discrete cracks providing for some control to the fracture process and increase the fracture energy. For quasi-brittle materials, such as concrete, loaded in tension the behaviour beyond the peak load can be described by the crack opening displacement (w) depending on the applied load (F) (Fig. 1).

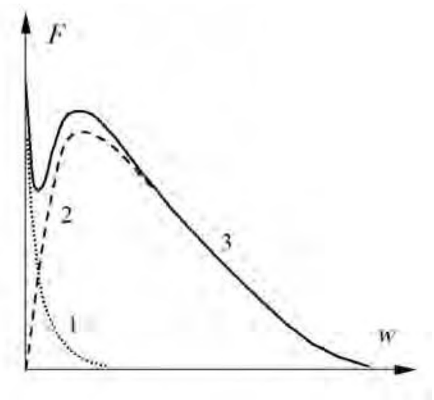

Figure 1. Crack opening for concrete (1), fibers (2) and SFRC (3).

As the principal benefits of the fibers are effective after concrete cracking, it is important to investigate the bridging phenomena in SFRC. There is a considerable residual strength of SFRC structures because the fibers guarantee a certain level of stress transfer between the faces of the crack.

Nevertheless, the nature of the stress transferring process at different fiber displacements needs to be studied. Is the effectiveness of fibers constant during the whole crack opening process? A numerical model, based on experimental data, needs to be developed, which will take into account the concrete strength, type of fiber, orientation angle and crack width. Part of this paper is allotted to represent the pullout tests performed to analyze the influence of the fiber type and orientation on the bridging process and to obtain the necessary material parameters for the numerical model.

Bridging models

To understand the bridging process in a FRC element, let us look at a small piece of concrete with a single arbitrary orientated steel fiber (see Figure 2). There is a micro crack in the matrix due to tensile stresses applied. The anchorage of the fiber is sufficient in both sides of the crack. The fiber has negligible reaction force until the bond-slip in the fiber-matrix interface has yet to be developed (w = 0).

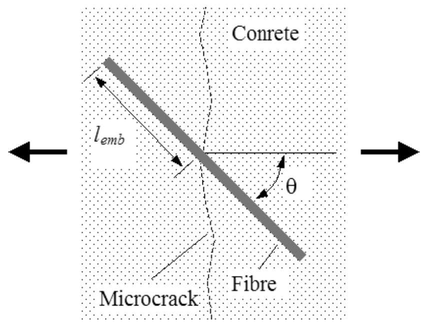

Figure 2. Bridging model at the beginning of crack formation.

When the crack width (w) increases, the fiber becomes active and deformation of the fiber occurs. The pulley approach (Aveston and Kelly, 1973) can be used to describe the bridging phenomena of a fiber crossing a cracked surface, with the assumption that the matrix at the exit point of the fiber is rigid. The model is shown in Figure 3. In this case the bond-slip of the fiber δ on the side of the shorter embedment is equal to the crack opening displacement ($\delta = w$).

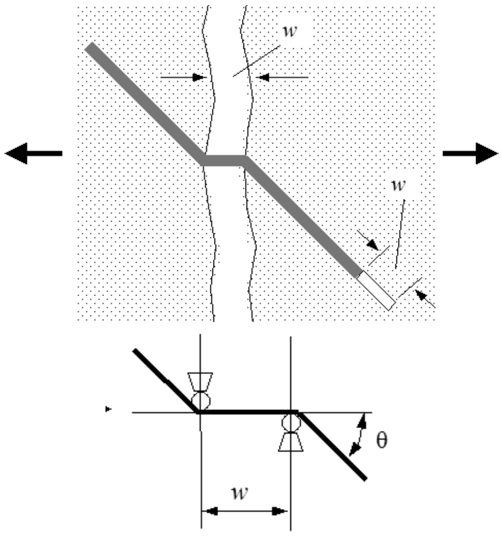

Figure 3. Bridging model based on pulley approach by Aveston and Kelly, 1973.

As the fiber-matrix interface has a negligible tensile strength, the fiber is able to damage a part of the matrix. In this case, the bridging phenomena of a fiber crossing a cracked surface could be described by using the pulley that is attached to the matrix via a spring (see Figure 4).

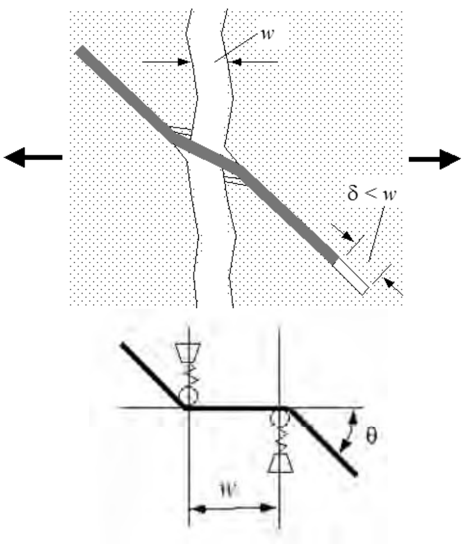

Figure 4. Modified bridging model – pulley attached to matrix via springs.

In the modified model the crack opening is greater than the fiber slip. The displacement for which the fiber becomes effectively involved in the tension carrying mechanism is the effective length w_{eff} which depends on the material parameters obtained from the fiber pullout tests for varying angle θ and fiber type (Brauns and Skadins, 2010; Fantilli et al., 2008).

The proposed model is based on the following basic assumptions.

The force, F_f, which can be taken by a single fiber is equal to zero when the crack width $w < w_{eff}$ and $w > l_{emb}$. Otherwise it can be found by the equation (1):

$$F_f = \pi d_f \tau_b \left(l_{emb} - w\right). \tag{1}$$

The effective length w_{eff} is determined at half of the maximum pullout force:

$$w_{eff} = w \quad \text{at} \quad F_{f,\max}/2\,. \tag{2}$$

The effective length or crack width at a certain orientation angle can be found by the equation (3):

$$w_{eff}(\theta) = K_1 + K_2 \tan\theta\,. \tag{3}$$

The fiber bond strength for $\theta = 0°$ is described by the equation (4):

$$\tau_b = \frac{F_{f,\max}}{\pi d_f l_{emb}}\,, \tag{4}$$

where in equations (1) to (4)

w – crack width or fiber displacement in pullout test;

$F_{f,max}$ – maximum single fiber pullout force;

K_1, K_2 – material parameters obtained from pullout tests;

θ – fiber orientation angle;

τ_b – fiber bond strength;

d_f – fiber diameter;

l_{emb} – fiber embedment length.

Pullout test

Short fibers act as a bridging mechanism over the crack. The behavior of fibers at the crack can be simulated by the single fiber pullout test (Figure 5). As the fiber orientation in FRC elements is random, the pullout test was performed for fibers with different orientation angles.

Specimen data

The tests were performed for four different types of fibers and four orientation angles. The fibers were concreted in small prisms with the dimensions of 40×40×60 mm.

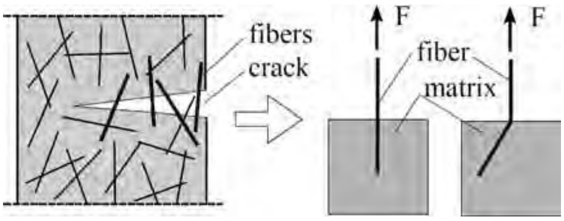

Figure 5. Pullout test as simulation of bridging process in cracked SFRC structure

The embedment length was 25 mm. The loosed part of the fibers was straightened. There were three specimens for each type and angle – all together 48 pieces. Concrete with very fine grains was used. The mean concrete strength was 55.1 MPa with the variation coefficient of 0.016.
Four different types of fibers were used, smooth (S), hooked (H), crimped (C) and flat ended (FE). The fiber diameter was 0.75 mm and length – 50 mm. The yield strength of the fiber steel was 1100 MPa.

Test setup

The tests were performed under closed looped conditions by controlling the position of the machine head and using the test speed 1 mm per minute. S9 type force transducer (max. load 50 kN) and three LVTD`s (HBM WETA1/2 mm) were used to record the data for force-displacement curves. The test setup is shown in Figure 6.

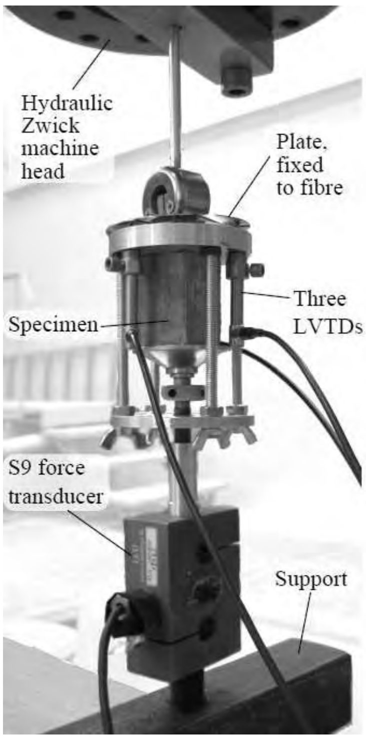

Figure 6. Pullout test setup.

Effective crack width

As it was mentioned before, the fibers become active after cracking. Nevertheless, not all of the fibers, crossing the developed crack, are effective at the very beginning of crack formation. From the test results it can be seen, that the fibers, which are more inclined, reach their maximal pullout force at a greater displacement (slip). That means that they will be involved in the bridging process when the crack is wide enough or when the width of the crack $w = w_{eff}$. It is assumed that the effective crack width (w_{eff}) can be found from the force-slip curves at the point $F_{f,max}/2$ (see equation (2)). For more inclined fibers the effective crack width is larger.
As the fibers at the angle of 90 degrees will have no effect in stress bridging, the tangent function is used to describe the relationship between the effective crack width and the fiber orientation angle. The agreement between the experimental results and theoretical function for each type of fibers is shown in Figure 7.

Critical value of the orientation angle

The fiber amount in concrete is one of the most important factors for post cracking behavior of a structure. There are several conditions that make a fiber effective if fulfilled:

- The fibers must be in the tension zone.
- They must be anchored enough (in both sides of the crack).
- The orientation of fibers cannot be parallel or close to parallel to the crack surface.
- The crack must be wide enough.

The SFRC structure design according to the crack width limit state requires ensuring comparatively small cracks in humid environment (0.3 mm). Although cracks can be wider in dry conditions and in the design of the ultimate limit state, they should be restricted to 3.5 mm (RILEM TC 162-TDF, 2003).
If the crack width is limited, then a certain portion of fibers, crossing the crack, will not be involved in the bridging process, for their orientation angle θ is too big. The angle θ_{crit} determining the boundary for the effective fibers can be found by the equation (5).

$$\theta_{crit} = \arctan\left(\frac{w - K_1}{K_2}\right) \tag{5}$$

At a certain crack width (w) only those fibers can be taken into account, which are inclined less than the critical angle (θ_{crit}).
The results of the equation (5) for different types of fibers and crack widths are given in Table 1.

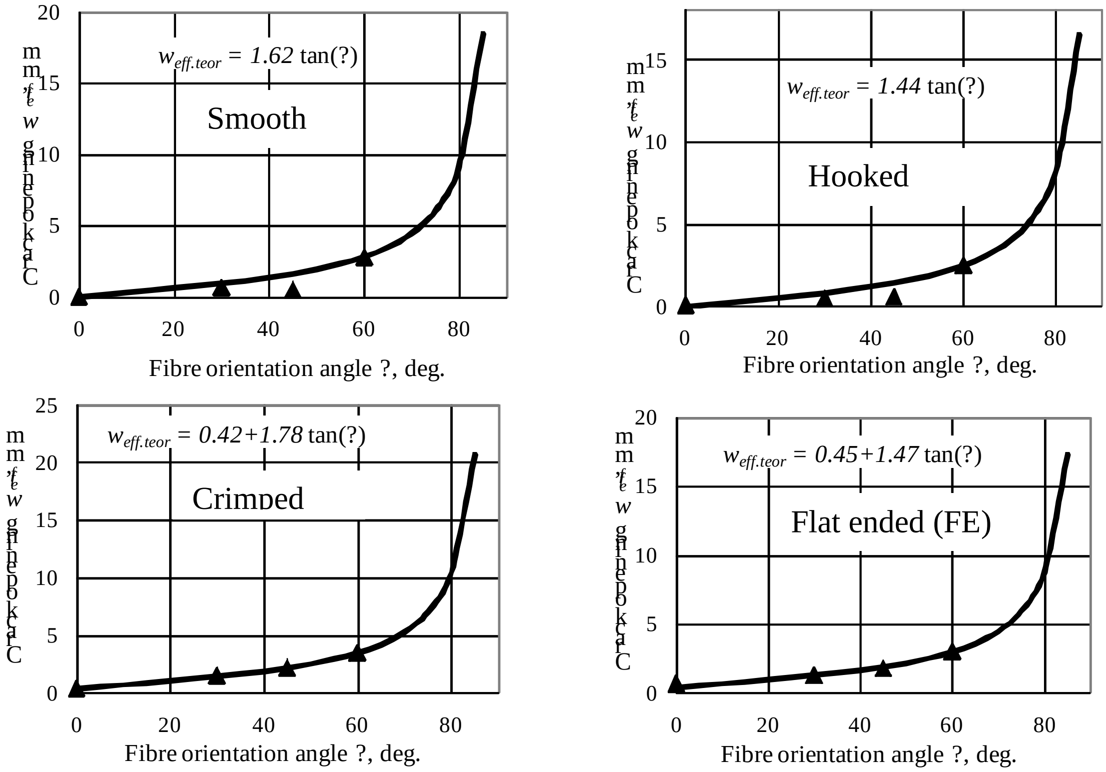

Figure 7. Effective crack width depending on fiber orientation angle.
▲ – experimental data; ▬ – theoretical curve.

Table 1

Critical angle depending on crack width

Fiber type	Critical angle θ_{crit} (°) for crack width *w* (mm)			
	0.5	*1.0*	*2.0*	*3.5*
Smooth	17	32	51	65
Hooked-ended	19	35	54	68
Crimped-round	2	18	42	60
Flat-ended	2	20	46	64

CONCLUSIONS

The steel fiber interaction with concrete in the single pullout test characterizes the overall behaviour of FRC under tensile stresses.

The complete fiber pullout was investigated for smooth, hooked, headed and crimped fibers with different orientation.

A numerical model is developed to simulate steel fiber crack bridging behaviour for different types of fiber and orientations.

For small cracks only fibers with small orientation angle are involved in the load bearing capacity.

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