FIBER BRIDGING

USER'S MANUAL

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1 Introduction

If you encounter any problems or bugs when using the program or if you have any question or reports and suggestions, please contact the author at michal.prinosil (at) fsv.cvut.cz.

1.1 About the program

This program was developed for fast and simple estimation of cohesive response of fiber-bridged crack in composite material with fiber reinforcement. The calculation is based on single fiber response and user obtains the relations between crack opening displacement and bridging stress (cohesive relation) as the result.

1.2 Acknowledgment

The author would like to thank his supervisor Petr Kabele for his support and advice during the software development. This work was carried out with financial support of the Czech Ministry of Culture, as part of the project no. DF11P01OVV008.

2 Getting started

2.1 Installation

The program was created in the software MATLAB[1] (version 2010b) and it can be used only in MATLAB environment. Other versions might work but have not been tested.

2.2 Program initialization

Download the zip archive and unzip it to a directory. In the main folder are files *main.m* and *inputFile.txt* and directory *files*. This directory contains all important files for the program.

The Graphic User Interface (GUI) of the program is started using the file *main.m*.

3 GUI description

If you successfully start the program, you will see the main window, which is vertically divided to two parts (Figure 1). The left part contains panel *Control*, the right part contains individual panels for input parameters. All panels are described in sections below.

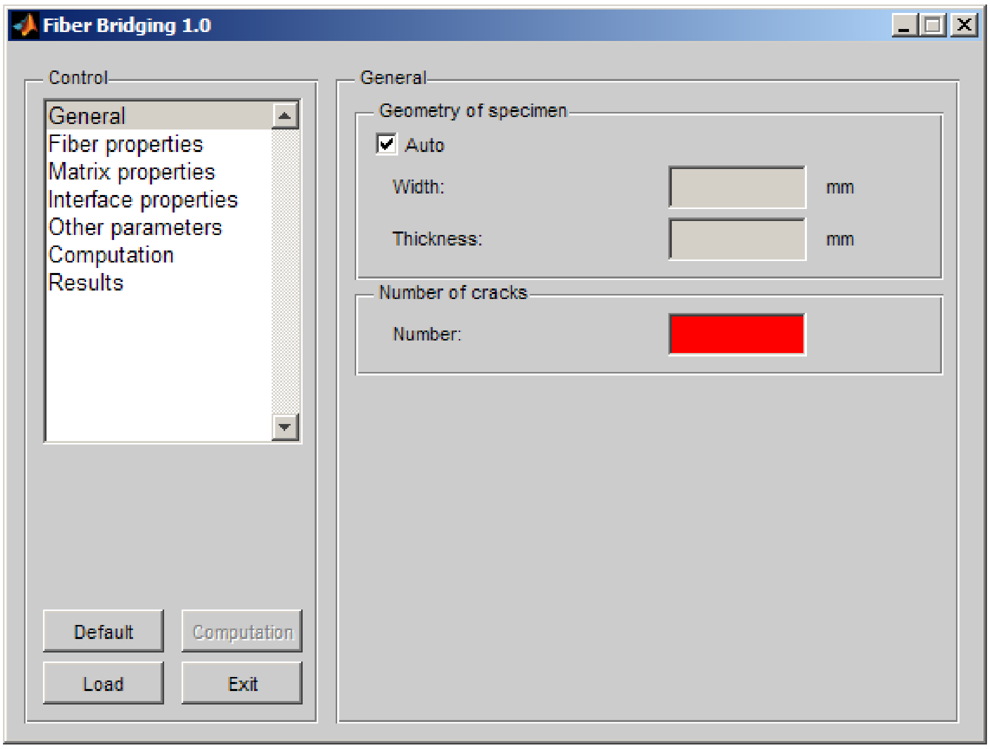


Figure 1: Main menu of the program

[1] http://www.mathworks.com

3.1 Panel Control

Panel *Control* contains the basic elements for handling program – one listbox and four buttons for basic operations.

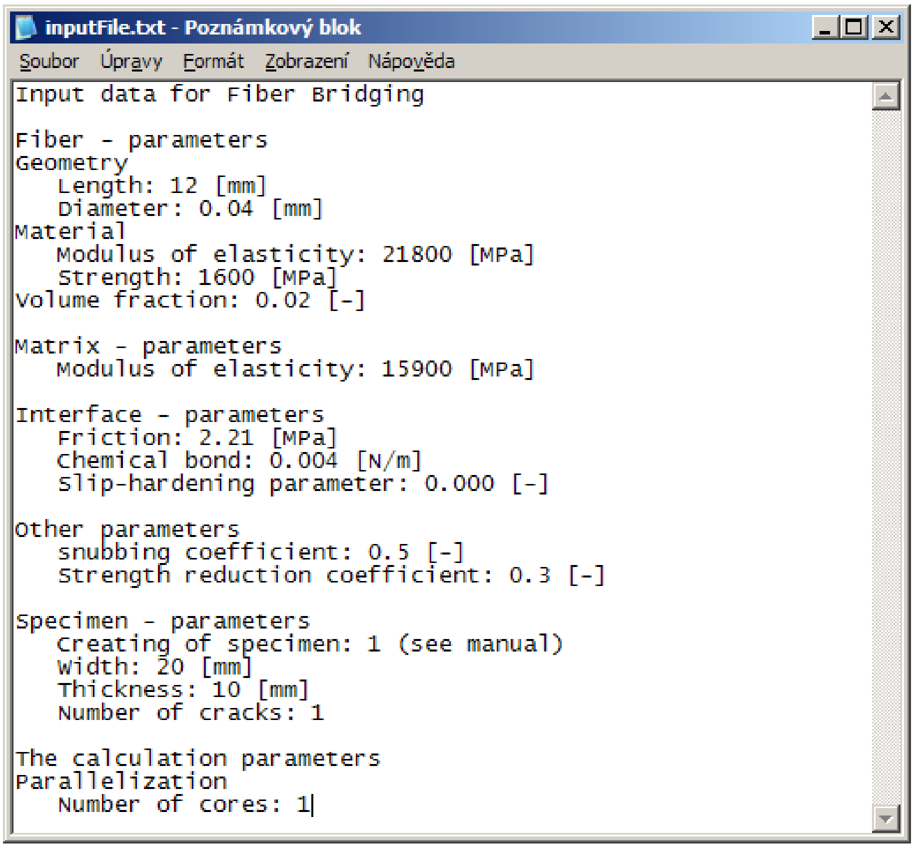
The main element is the listbox that allows you to change the right part of the main window. When selecting the item in the listbox the panel is automatically changed.

Using the button *Default*, basic values are loaded into the program. These values correspond to cementitious composite reinforced with PVA fibers [1]. They serve as a sample and user can modify these values.

A similar feature has the button *Load*. Using this button the values can be loaded from an input file. The sample file *inputFile.txt* contains the values corresponding again to cementitious composite with PVA fibers. The structure of this file must be strictly observed. Only the values of individual parameters can be changed. An example of input file is shown in Figure 2.

The button *Computation* starts the calculation. After pressing the right panel is automatically switched to the panel *Results* and the mouse pointer is for calculation switched to the hourglass. It may takes up to several minutes. Then the results are shown in the graph (3.8). This button is disabled until all values of program are correctly filled. The bad value indicates red color of the box (see Figure 1 – Number of cracks). They can be filled only by numeric values with decimal point represented by dot (“.”).

Button *Exit* terminates the program.




```
Input data for Fiber Bridging

Fiber - parameters
Geometry
   Length: 12 [mm]
   Diameter: 0.04 [mm]
Material
   Modulus of elasticity: 21800 [MPa]
   Strength: 1600 [MPa]
Volume fraction: 0.02 [-]

Matrix - parameters
   Modulus of elasticity: 15900 [MPa]

Interface - parameters
   Friction: 2.21 [MPa]
   Chemical bond: 0.004 [N/m]
   Slip-hardening parameter: 0.000 [-]

Other parameters
   Snubbing coefficient: 0.5 [-]
   Strength reduction coefficient: 0.3 [-]

Specimen - parameters
   Creating of specimen: 1 (see manual)
   Width: 20 [mm]
   Thickness: 10 [mm]
   Number of cracks: 1

The calculation parameters
Parallelization
   Number of cores: 1
```

Figure 2: An input file

3.2 Panel General

This panel is the first for input values (Figure 1). It deals with the geometry of the test specimen. Width and thickness of the cross section can be entered manually or automatically. Using the automatic generation both dimensions correspond to 2,5-times the fiber length. Value corresponding 2,5 or higher should not affect the results, because the fibers in the outer layer are shortened by the edges of the specimen.

Height of the specimen is calculated from the number of cracks. Between the cracks themselves and between the cracks and border of the specimen is left distance corresponding 1,5-times the fiber length so that the results were independent.

In prismatic volume corresponds to width, thickness and height the fibers are generated.

3.3 Fiber properties

In this panel you can set the geometric and material properties of fibers and also their volume fraction (Figure 3). From the geometrical properties are important length and diameter of fiber. These values are given in millimeters. From the material properties are important Young's modulus of elasticity and strength. These values are given in megapascals.

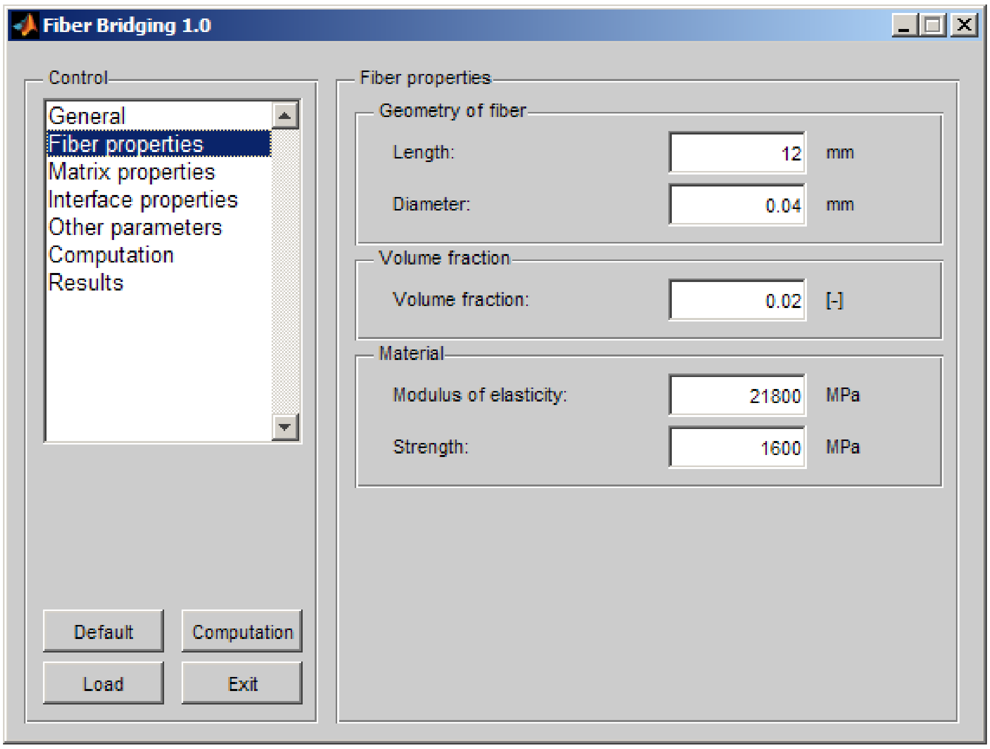


Figure 3: Panel Fiber properties

3.4 Matrix properties

Here you enter only Young's modulus of elasticity of matrix, which is given in megapascals (Figure 4).

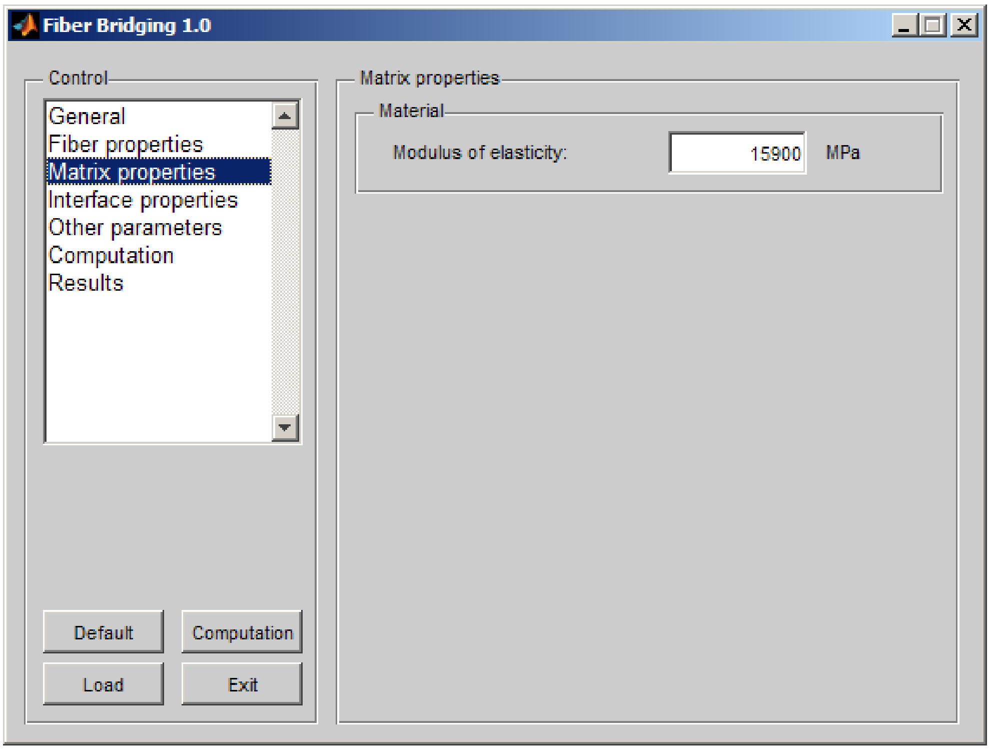


Figure 4: Panel Matrix properties

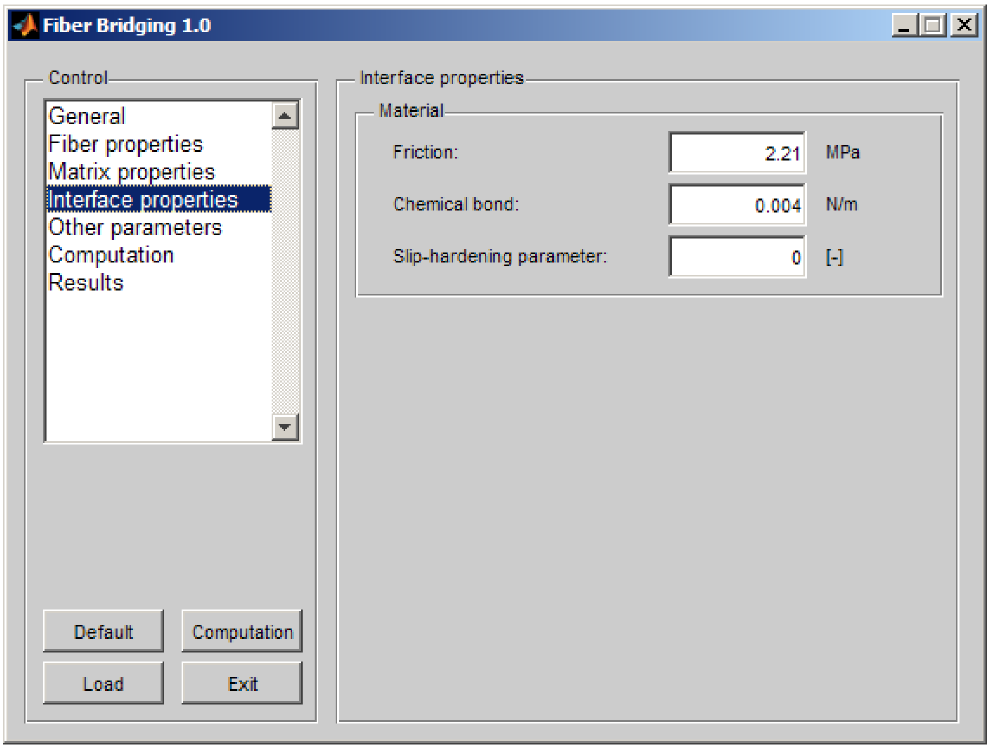


Figure 5: Panel Interface properties

3.5 Interface properties

The interface between fiber and matrix is characterized by three parameters – chemical bond, frictional stress and slip-hardening parameter (Figure 5). Theoretical background is in section 4.1.

3.6 Other parameters

These two parameters describe the influence of the angle between the axis of the fiber and normal to the surface of crack (Figure 6). Snubbing coefficient describes the effect of angle on the force in the fiber. Strength reduction coefficient describes the effect of angle on the strength of fiber (section 4.2).

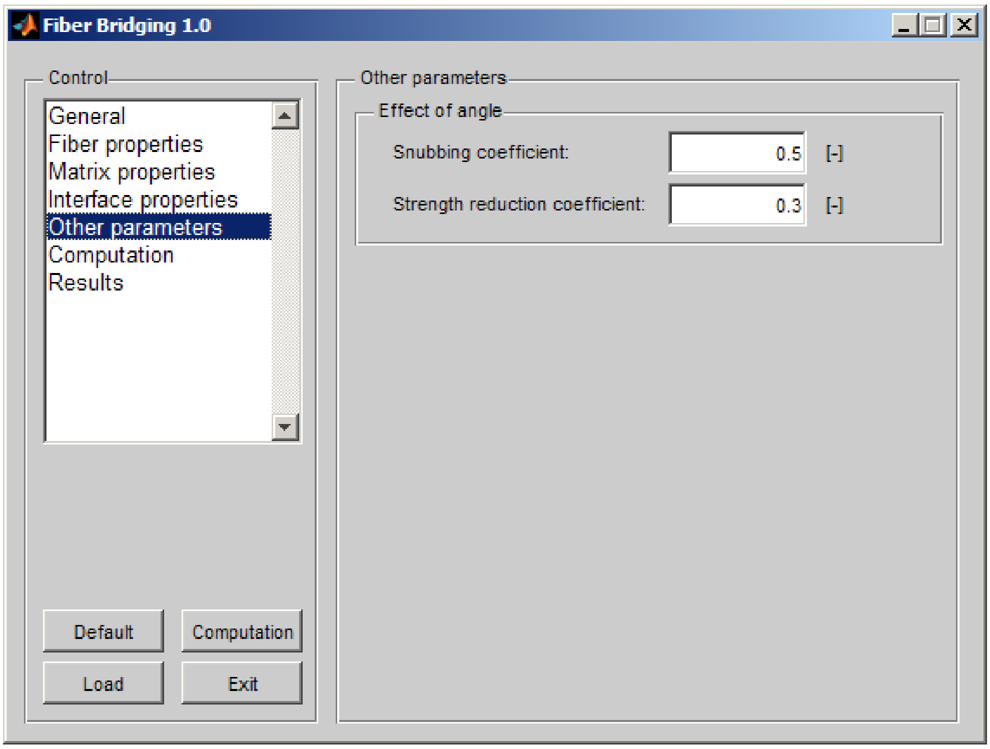


Figure 6: Panel Other parameters

3.7 Panel Computation

On this panel you can set how many cores of processor will be involved in the calculation (Figure 7).

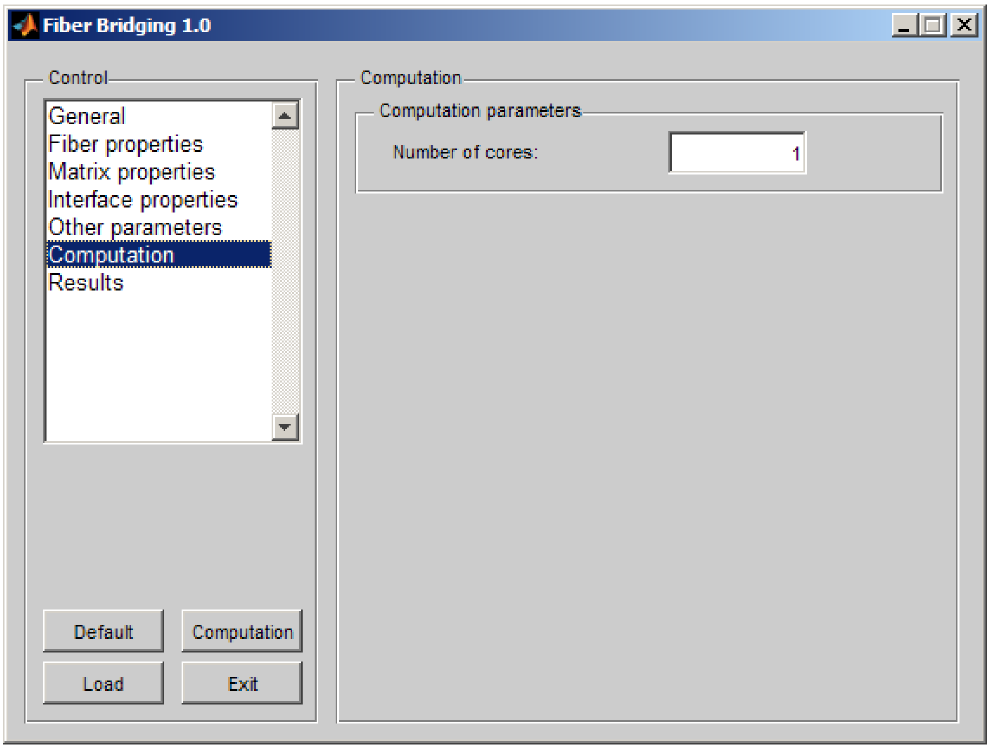


Figure 7: Panel Computation

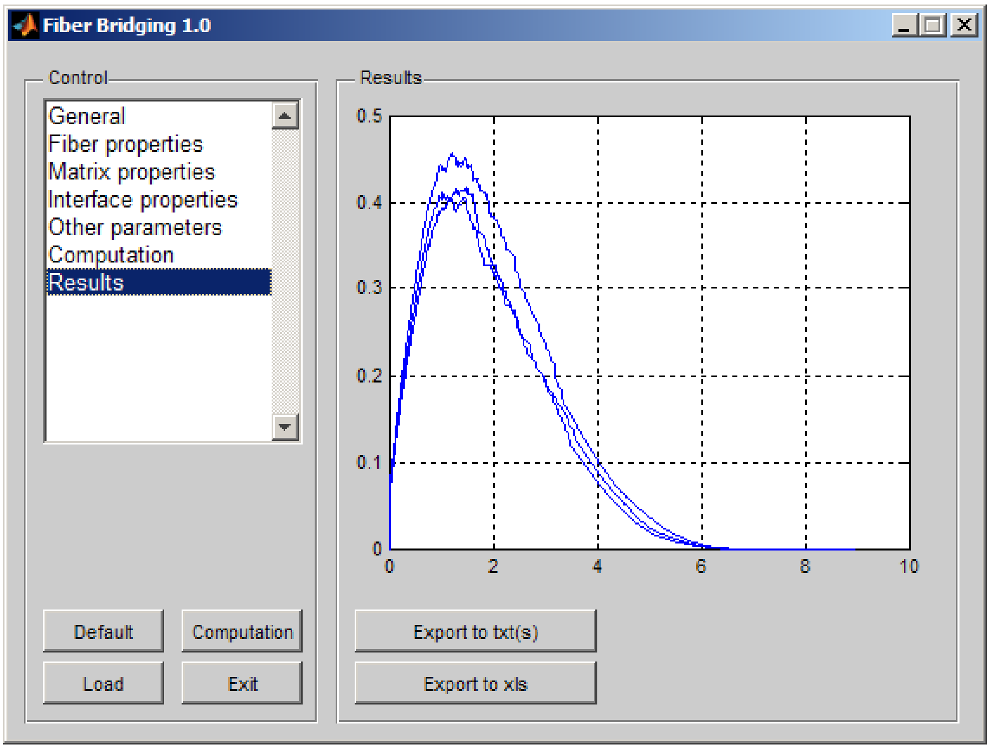


Figure 8: Panel Results

3.8 Panel Results

This panel consists of the graph plotting the results and the two buttons for data exporting (Figure 8). The graph shows the results in relation between bridging stress and crack opening displacement (cohesive relation).

Data can be exported either to a text file (each result into single file) or to Excel file (first column corresponds to crack opening displacement and other columns to bridging stress). Export buttons are disabled until the first calculation is performed.

4 Theory

4.1 Fiber-matrix interaction

When tensile strength is achieved in matrix due to tension or shear, material undergoes cracking. Formation and opening of cracks is prevented by the fiber reinforcement. During this process, fibers bridging the crack are elastically stretched and pulled out of the matrix. The process of extracting of fibers from the surrounding matrix can be divided into two separate stages.

The first stage is fiber debonding – propagation of tunnel crack along the interface between fiber and matrix. The tunnel crack spreads from the crack surface to the embedded end. Debonding is resisted by fiber-matrix chemical bond *Gd*. The debonded part of the fiber is stretched that is constrained by frictional stress τ_0 at the fiber-matrix interface. The debonding is completed when the debonded part of fiber reaches the embedment length L_e. In [2] we can found the formula describes relationship between force *P* on the pulled end of the fiber and the displacement *u* at the same point:

$$P_{deb} = \sqrt{\frac{\pi^2 \tau_0 E_f d_f^3 (1+\eta)}{2} u + \frac{\pi^2 G_d E_f d_f^3 (1+\eta)}{2}} \tag{1}$$

where E_f is Young's modulus of elasticity of the fiber, d_f is the fiber diameter and the η is:

$$\eta = \frac{E_f V_f}{E_m V_m} \tag{2}$$

where V_f is fiber volume fraction, V_m is matrix volume fraction ($V_m = 1 - V_f$) and the E_m is Young's modulus of elasticity of the matrix.

When a fiber is completely debonded, a pull-out phase follows. During this stage, the fiber slips out from the matrix. This is constrained only by frictional stress τ_0 acting on the fiber-matrix interface, whose are is reduced due to extraction. The frictional stress can either increase or decrease with increasing displacement *u*, which is related to the fiber-matrix interaction (abrasion of the fiber or the matrix, etc.). This interaction is expressed by fiber-matrix slip-hardening parameter β. The elongation of the fiber is very small to compare to the slip and therefore the fiber is considered as perfectly rigid in this stage. The relationship between *P* and *u* derived in [2] is:

$$P_{pull} = \pi d_f \tau_0 \left(1 + \frac{\beta(u - \delta_c)}{d_f}\right)(L_e - u + \delta_c) \tag{3}$$

where δ_c corresponds to displacement at the end of the debonding stage:

$$\delta_c = \frac{2\tau_0 L_e^2 (1+\eta)}{E_f d_f} + \sqrt{\frac{8 G_d L_e^2 (1+\eta)}{E_f d_f}} \tag{4}$$

4.2 Effect of the angle between the fiber axis and normal to the surface of crack

When a fiber is not perpendicular to the crack surface, it affects the fiber response. The fiber snubs against the matrix at the point, where the fiber exits from the matrix. This effect corresponds to the frictional pulley [3] and the pullout force can be expressed as:

$$P(\varphi) = P(0)e^{f\varphi} \tag{5}$$

where *P(0)* is force from Eq. (1)-(2), φ is the angle between the fiber axis and normal to the crack surface and *f* is snubbing coefficient. The second effect is the tensile strength reduction due to angle [4]:

$$\sigma_f(\varphi) = \sigma_f(0)e^{-g\varphi} \tag{6}$$

where σ_f is the tensile strength at zero angle and *g* is the strength reduction coefficient.

4.3 Bridging stress-crack opening relation

The relation between bridging stress σ_b and crack opening displacement δ (cohesive relation) is calculated as the sum of all forces in fibers bridging a crack divided by the crack area (defined by width *b* and thickness *t* of the specimen – see 3.2):

$$\sigma_b(\delta) = \frac{\sum P(\delta,\varphi)}{bt} \tag{7}$$

In the calculation is considered debonding (and possible pulling) of fiber on both sides of the crack [5]:

$$\delta = u_1 + u_2 \tag{8}$$

where u_1 and u_2 are individual displacements of the fiber at the exit points. It plays important role when slip-hardening behavior is present. Furthermore, possible fiber rupture is considered, which occurs when stress in a fiber reaches its tensile strength.

At the beginning, the individual fibers are generated in the specimen with dimensions defined in panel General (section 3.2). Their number is calculated from the specimen volume, the volume of one fiber and the volume fraction of fibers in composite material. Then the fibers intersecting the crack surface are chosen and the cohesive relationship by the Eq. (7)-(8) is calculated. The calculation is controlled by crack opening displacement δ.

5 References

[1] KABELE, P. Multiscale framework for modeling of fracture in high performance fiber reinforced cementitious composites. *Engineering Fracture Mechanics*. 2007, vol. 74, 1-2, pp. 194-209.

[2] LI, V.C., LEUNG, C.K.Y. Steady state and multiple cracking of short random fiber composites. *Journal of Engineering Mechanics*. 1992, vol. 188, 11, pp. 2246-64.

[3] LI, V.C. Post-crack scaling relations for fiber-reinforced cementitious composites. *Journal of Materials in Civil Engineering*. 1992, vol. 4, 1, pp. 41-57.

[4] LIN, Z., KANDA, T., LI, V.C. On Interface Property Characterization and Performance of Fiber Reinforced Cementitious Composites. *Concrete Science and Engineering*. 1999, vol. 1, pp. 173-184.

[5] Yang, E., et al. Fiber-Bridging Constitutive Law of Engineered Cementitious Composites. *Journal of Advanced Concrete Technology*. 2008, vol. 6, 1, pp. 181-193.