19th International Conference
ENGINEERING MECHANICS 2013
Svratka, Czech Republic, May 13 – 16, 2013

NUMERICAL MODEL FOR DUCTILE FIBER-REINFORCED CEMENT-BASED COMPOSITE

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Summary: *Strain Hardening Cement-based Composite (SHCC) is a type of High Performance Concrete that was developed to overcome the brittleness of conventional concrete. The primary objective of this contribution is to verify a developed constitutive model (Vorel and Boshoff, 2012) intended to be utilized in simulations of structural components with SHCC under different types of loading conditions.*

Keywords: ***Strain Hardening Cement-based Composite (SHCC), rotating crack model, three-point bending test***

1. Introduction

At the beginning of the 21st century, civil engineers more than before face the often-contradictory demands for designing larger, safer, and more durable structures at lower cost and shorter time. Concrete has been used over many centuries as a reliant, fairly durable building material. Two of the main advantages of concrete are that it has a high compressive strength and can be cast on the construction site into almost any shape and size. The most prominent disadvantages of concrete are the brittleness during failure and the low tensile strength. The low tensile strength is usually compensated with steel reinforcing, but wide cracks allowing corrosion of steel still occur during the normal use of concrete. These cracks lead to durability problems and cause faster structural degradation.

The Strain Hardening Cement-based Composite (SHCC) is a type of High Performance Concrete (HPC) that was developed to overcome the brittleness of conventional concrete. Even though there is no significant compressive strength increase compared to conventional concrete, it exhibits superior behavior in tension achieved by the relatively low addition (about 2% by volume) of short random synthetic fibers. It has been shown to reach a tensile strain capacity of more than 4% during a pseudo strain hardening phase (Li and Wang, 2001; Boshoff and van Zijl, 2007). This strain hardening is achieved by the propagation of fine, closely spaced cracks with crack widths normally not exceeding $100\mu m$ (Li and Wang, 2001). These fine cracks, compared to large localized cracks found in conventional concrete, have the advantage of increased durability.

Several authors have simulated SHCC mechanical behavior with the Finite Element Method (FEM). Kabele (2000) formulated a smeared crack model to simulate the mechanical behavior

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of SHCC. Another model proposed by Han et al. (2003) was created to simulate the cyclic loading of SHCC. This study was performed to test the improvement of structural response if SHCC elements are used to dissipate energy during earth-quake loadings. Simone et al. (2003) used an embedded discontinuity approach for the final material softening and concluded that it did not satisfactorily simulate the experimental results of SHCC. Boshoff (2007) created a simple damage mechanics based model for the tensile behavior of SHCC.

The primary objective of the presented research is to verify a constitutive model presented in (Vorel and Boshoff, 2012) that is intended to be used in simulations of structural components with SHCC under different types of loading conditions. In particular, different flexural tests are examined to verify the constitutive model analyses and show advantages and disadvantages of the model. Therefore, the three-point bending test is introduced using parameters based on the tensile tests and data presented by Boshoff (2007). The obtained results are compared with experimental data.

The paper is organized as follows. The basic features and definitions of the model are briefly described in Section 2.. Section 3. deals with the finite element simulations of studied experiments. Finally, the concluding remarks and discussion are provided in Section 4..

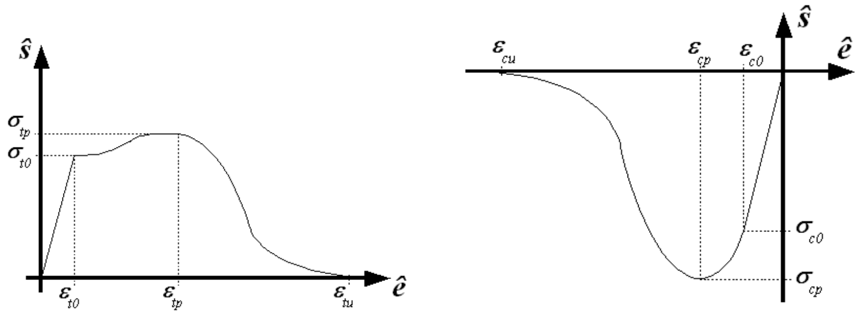
2. Numerical model description

In this section the main features of the utilized numerical model are briefly described. The complete description and definition of the model can be found in (Vorel and Boshoff, 2012). To model the specific behavior of SHCC in tension, the application of classical constitutive material models used for quasi-brittle materials is not straightforward. The utilized numerical model is based on a rotating crack assumption to capture the strain hardening and softening, the multiple cracking, the crack localization and multiple orthogonal crack patterns (Suryanto et al., 2008). A complete description of the rotating crack model can be found, e.g., in (Rots, 1998).

Note that the rotating crack model evaluates a given strain state and generates the inelastic strain in the principal directions of the strain and does not automatically include the effect of Poisson's ratio as the stress is evaluated on the basis of individual principal strains. To allow the residual deformations and to account for the Poisson ratio effect a new approach is employed where the effective principal strain is used to determine the equivalent stress from the simplified uniaxial stress-strain diagram (Fig. 1). The effective principal strain is based on the principal strain which is free of inelastic deformations caused during the stress state change. The evolution of inelastic strain is assumed to be linearly dependent on the previously reached maximum strain for the elastic and hardening part and linearly dependent on the crack opening for the softening branch. This simplification correspond well with experimental results (Vorel and Boshoff, 2012).

In general, the model takes into account the following items:

- strain hardening and softening in tension as well as in compression,
- nonlinear unloading,
- nonlinear loading after stress state change - crack closing,
- the effect of Poisson's ratio.



(a) (b)

Figure 1: Virgin loading: (a) Tension, (b) compression

3. Numerical simulations

The model briefly described in the previous section and in detail in (Vorel and Boshoff, 2012) is implemented in the open source finite element code OOFEM (Patzák and Bittnar, 2001). Isoparametric four-node quadrilateral plane-stress finite elements with four integration points (PlaneStress2d) are employed for the discretisation of the numerical models presented in this paper. Due to the lack of a reverse cyclic loading some parameters are set up using the engineering judgement of the authors as this will not have a significant influence on the presented results. The available tensile tests for the same mixture as beams are used to set up the parameters describing tension (Table 1).

The aforementioned numerical model is used to obtain the force-deflection diagrams of three-point bending tests. Two different numerical studies for two different sizes of beams (Fig. 2) are presented in this paper. First, the mesh-dependency of the model is investigated by varying the element size (5 mm and 1.5 mm). Second, the edge-effect caused by the aligned fibers along the bottom surface of beams is studied. The tensile strength and the strain hardening capacity in the region of the aligned fibres increase, see Table 1 and (Boshoff, 2007), and so the 3 mm thick layer with enhanced material properties is introduced at the bottom of the finite element (FE) models.

Table 1: Material model parameters (* parameters experimentally obtained or presented in (Boshoff, 2007), $(\cdot)$ parameters of the surface layer with aligned fibres)

General			Tension			Compression		
Param.	Value		Param.	Value		Param.	Value	
E	9200^*	MPa	σ_{t0}	1.95^* (2.23^*)	MPa	$\|\sigma_{c0}\|$	14.0	MPa
ν	0.35^*		ε_{tp}	0.048^* (0.060^*)		$\|\varepsilon_{cp}\|$	0.0025	
			σ_{tp}	3.0^* (3.5^*)	MPa	$\|\sigma_{cp}\|$	17.6^*	MPa
			w_t	6.0^*	mm	$\|\varepsilon_{cu}\|$	0.4	
			a_t	3.0		d_c	50.0	mm
			b_t	0.8^*		a_c	3.0	
			b_t^{cl}	0.6		b_c	0.8	
						b_c^{cl}	0.8	

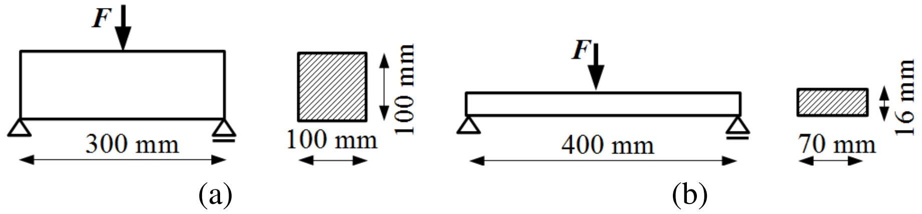


Figure 2: Schemes and dimensions of three-point bending tests

4. Discussion and conclusions

In this paper a two-dimensional numerical model for Strain Hardening Cement-based Composites is studied. The accuracy of the introduced approach is investigated by means of a three-point flexural tests. The numerical simulations match reasonably the experimental data for both beam types. The mesh-dependency investigation revealed certain influence of the mesh size on the softening part of the force-displacement curve shown in Figs. 3(a-b). On the other hand, the influence of the extra layer representing the aligned fibers along the surface of the beam is not strongly pronounced for any of the mesh sizes of the beam 100x100x300 mm, see Fig. 3(a-b). As expected, the influence of enhanced layer is more pronounced for the beam 16x70x400 mm where it represents significant portion of the beam height (Fig. 3(c)).

Acknowledgment

The financial support provided by the GAČR grant No. 105/12/P353 is gratefully acknowledged.

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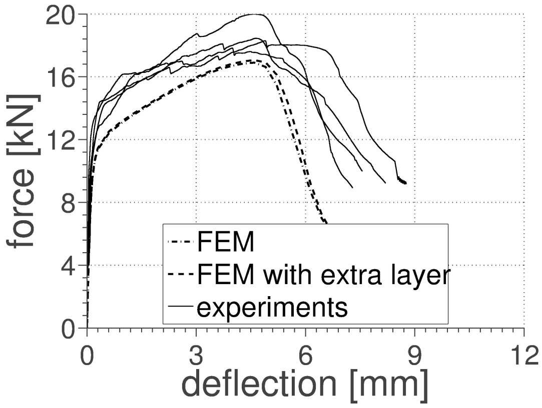
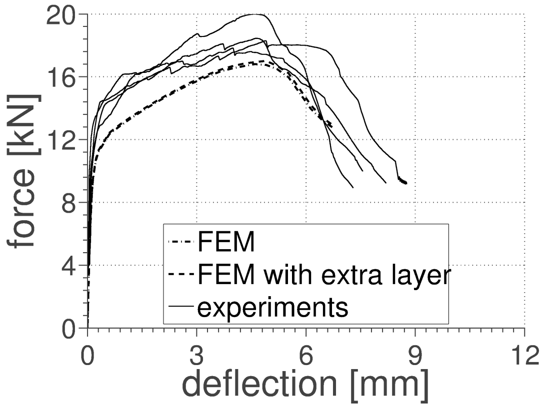
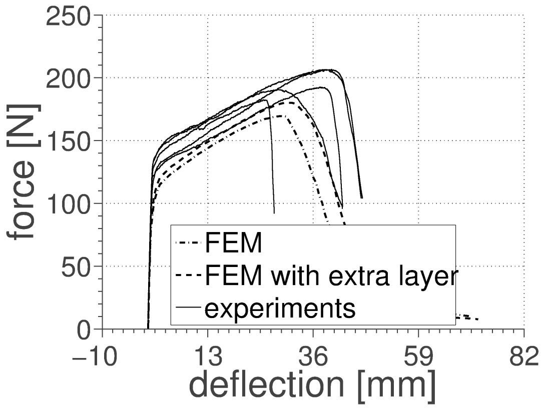


(a)



(b)



(c)

Figure 3: Three-point bending test: a) beam 100x100x300 mm, mesh size 5 mm, b) beam 100x100x300 mm, mesh size 1.5 mm, c) beam 16x70x300 mm mm, mesh size 2.5 mm

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