ON MODELING EXPERIMENTS WITH FRC IN ATENA SOFTWARE

Jan Eliáš [1], Miroslav Vořechovský [2]

Abstract

The article is primarily focused on negative effect of perfect numerical model symmetry when it is used for inverse identification of material model parameters for FRC. It is shown that if the model constructed in finite element (FEM) package is perfectly symmetric (homogeneous distribution of local material parameters, geometry, boundary conditions), the identified material parameters may significantly differ from those obtained with nearly identical model with disturbed symmetry. By the identified parameters, we mean parameters leading to model response identical with experimentally obtained response. The presented numerical study is based on previous work by the authors and computational results are compared with experimental series on modulus of rupture test of FRC. In particular, we present comparisons of four point bending beams. In addition, the paper discusses the choice of an ideal shape of tensile softening for the used FRC material.

Keywords: symmetry of four point bending model; inverse identification of material law; FRC; tensile softening.

1 Introduction

One of the important steps while designing structures made of non-traditional materials such as special forms of FRC is the virtual simulation of structural response. The complex behaviour of the composite material at hand (short glass fibres embedded in quasibrittle matrix) calls for advanced nonlinear modelling based on fracture mechanics. In this article, the authors focus on modelling of mechanical response using the ATENA software [1]. In order to predict the structural response numerically, one needs the material parameters of FRC to be used in the model. The best choice to find material parameters is to match the experimentally obtained response with the virtual response. This step is called inverse identification of material parameters. This paper documents possible errors when working with spuriously symmetric and homogeneous models in the identification process and finds a remedy in various forms of symmetry disturbances.

The article starts with description of a large set of specimens (beams) made from FRC with glass fibres AR Glass (CEM FIL Anticrack HP) and the experiments (sec. 2). Next, the paper continues with experimental results and simulation results obtained with

1) BUT - Faculty of Civil Engineering, Institute of Structural Mechanics, Veveří 95, 602 00 Brno Czech Republic, e-mail: elias.j@fce.vutbr.cz

2) BUT - Faculty of Civil Engineering, Institute of Structural Mechanics, Veveří 95, 602 00 Brno Czech Republic, e-mail: vorechovsky.m@fce.vutbr.cz

Atena software in sec. 3. We discuss an ideal shape of tensile softening. The last section 4 documents differences in four point bending model results when using homogenous distribution of material properties over the whole specimen and simulation with added initiator of localization.

2 Experiments

The authors performed mechanical testing of 279 FRC specimens with variable sizes and geometries, see fig. 1. Only a part of the experiments is presented here. The important fact is that four point bending beams were loaded by two equal forces and thus asymmetric deformation is enabled.

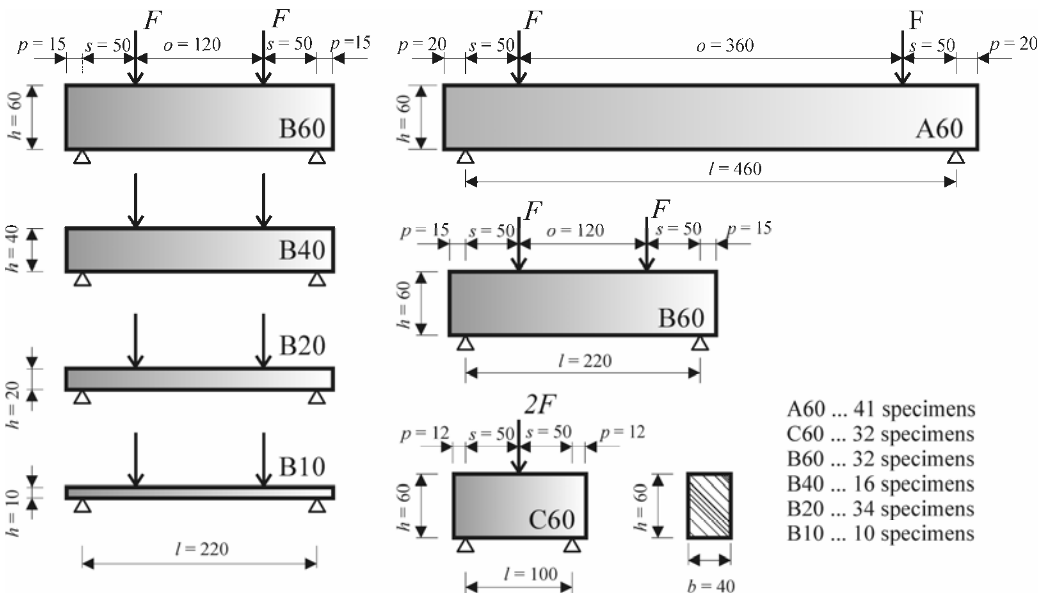

Fig. 1 Sketch of the specimens: geometry, boundary conditions and type labelling, numbers in parentheses denote the number of specimens for each type; see [2] for detailed documentation.

3 Identification of material law

The studied series of FRC specimens was solely damaged by tension in the bottom half of the beam depth. Therefore, we focus only on the tensile properties of the material law. Atena software offers several material models [1], *3D Nonlinear Cementitious 2 User* being the most flexible. Unfortunately, the authors faced countless problems while using the model (lots of error messages probably due to non-professional usage). Therefore it was decided to use *SBeta* material model which has linear pre-peak part of the load-strain diagram and three possible shapes of the descending branch: linear, exponential or SFRC (steel fibre reinforced concrete softening); all three are plotted in fig. 2a,b and c.

In a recent publication [2] it is showed that the exponential and linear softening diagrams are decreasing too steeply after the peak stress to be able to match the experimentally obtained responses. Similarly, SFRC softening has too sudden end. The best tensile softening obtained by playing with the variable *3D Nonlinear Cementitious 2*

User model is sketched in fig. 2d. Because there is no real possibility to routinely use this softening in Atena 2D, we used approximate rectangular softening derived from SFRC, see the dotted line fig 2d.

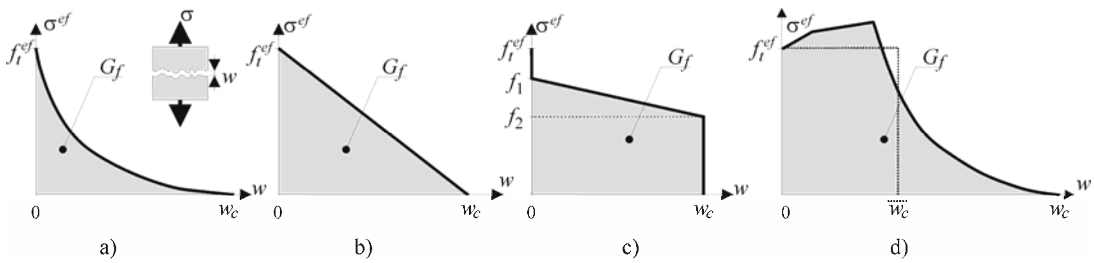

Fig. 2 Types of tensile softening in material model SBeta: a) exponential, b) linear, c) SFRC. d) Proposed ideal tensile softening for studied FRC.

The mean value of *E* modulus for all specimen types was identified roughly as 16.3 GPa. To fit the experimental response in Atena 2D software, only two parameters: f_t (tensile strength) and G_F (fracture energy) were varied. Simulation models have homogenous isotropic material with constant material characteristics over all finite elements. Responses of these models are plotted in figures presented in sec. 4. Identified parameters vary for each specimen type; overall approximate results are summarized in table 1.

		mean value	standard deviation	
modulus	E	16.3	1.63	GPa
tensile strength	f_t	7.0	0.7	MPa
Atena fracture energy	G_F	60	6	J/m^2

Tab. 1 Overall results

4 Spurious symmetry in four point bending test

The simulations described in the previous section were obtained with perfectly symmetric model. The virtual specimens were damaged in bottom face over the whole bending span and the final mechanism of failure can be represented by two major cracks under concentrated loads, see fig. 6 right-top. There is a huge energy dissipation associated with such failure mechanisms (involving large process zones). Since the real material is not ideal elastic-plastic and also not ideally homogeneous, there should be occur only one process zone with one macro crack as sketched in fig. 6 right-bottom. This could be suitably simulated e.g. by the use of sophisticated statistical models such as random fields of local material parameters [3]. However, such computations are too complicated for our purpose (it requires unavailable information on correlation length etc.). To show the anticipated effect of spurious model symmetry and the need to trigger fracturing by spatial strength variation we describe a model with simple crack initiator.

4.1 Variations of local tensile strength

In order to make the computational model asymmetric and make the model initiate cracks in small region, we make modifications of the material tensile strength f_t. It only suffices to modify the local strength in the boundary layer of cracking which is less than half beam depth in our case. There are two options: either to weaken a small portion of material and keep the rest or reinforce the whole bottom boundary except for a small portion, see fig. 4 for illustration. The two options will be called simply 'weak' and 'strong' and the shadowed weaker/stronger material tensile strength is denoted as $f_{t,p}$. The finite element mesh sketched in fig. 4 is illustrative only. In order to study the effects of (i) size of the weak/strong region n and (ii) the value of $f_{t,p}$, we performed a parametric study over a range of values. In the numerical simulations the weak/strong region was kept rectangular spanning the area of $n \times n$ elements; n being the number of elements spanning the rectangle edge. To obtain consistent results the finite element mesh, geometry, boundary conditions, loading step size and solution parameters were kept identical throughout the study, see [4] for reasons. The tensile strength f_t of the basic material was 7.0 MPa.

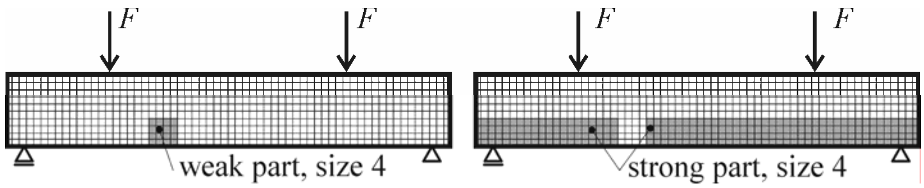

Fig. 4 Model with weak/strong part to simulate an asymmetric failure mode

Results of the numerical study are presented in fig. 5 using a surface for nominal strength as a function of size n and strength $f_{t,p}$. Almost every size and strength of initiator leads to an asymmetric failure. The only exception is when n=1 and $f_{t,p}$ in the range 6.75 – 7.0 MPa: under these conditions the initiator is too small and strong and the failure mode remains symmetric, see fig. 5. In the figure, the symmetric failure is manifested by the elevated edge of the graph. The nominal stress is generally decreasing with increasing size n of weak initiator. The only exception is the jump from size n=1 to n=2 which is accompanied by increase of the nominal strength. The reason is that when n=2, both weakened elements undergo cracking and dissipate energy. The same applies when n>2. When the initiator is small (n=1) the nominal stress is nearly insensitive to $f_{t,p}$. This is visualized through fig. 6 showing simulation responses for initiator of size 1 with variable tensile strength. Major differences are between symmetric and asymmetric failure responses, not between asymmetric failure responses with different initiator strength.

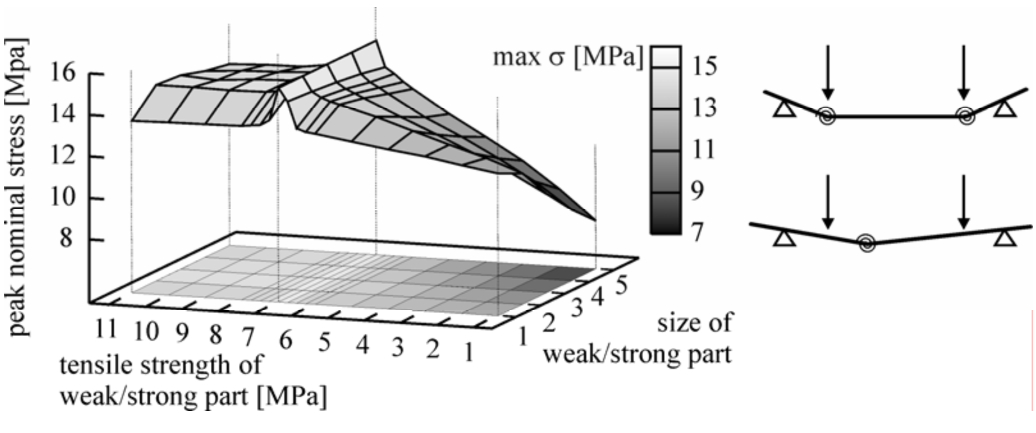

Fig. 5 Right: Symmetric and asymmetric failure. Left: Dependence of peak nominal stress on size and strength of initiator

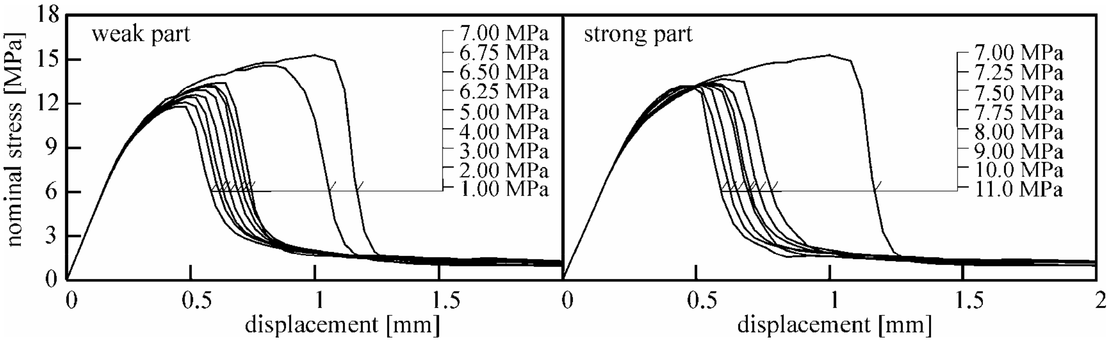

Fig. 6 Responses of model B20 with initiator of size 1 of variable tensile strength

4.2 Symmetric and asymmetric simulation: impact on identified fracture energy G_F

In this section we present results for symmetric and asymmetric simulations for various specimen geometries/sizes. The target is to show the differences in identified fracture energy that must be used to match the experimental results. All specimens are modelled with initiator of size 1 and tensile strength $f_{t,p} = f_t - 1$ MPa.

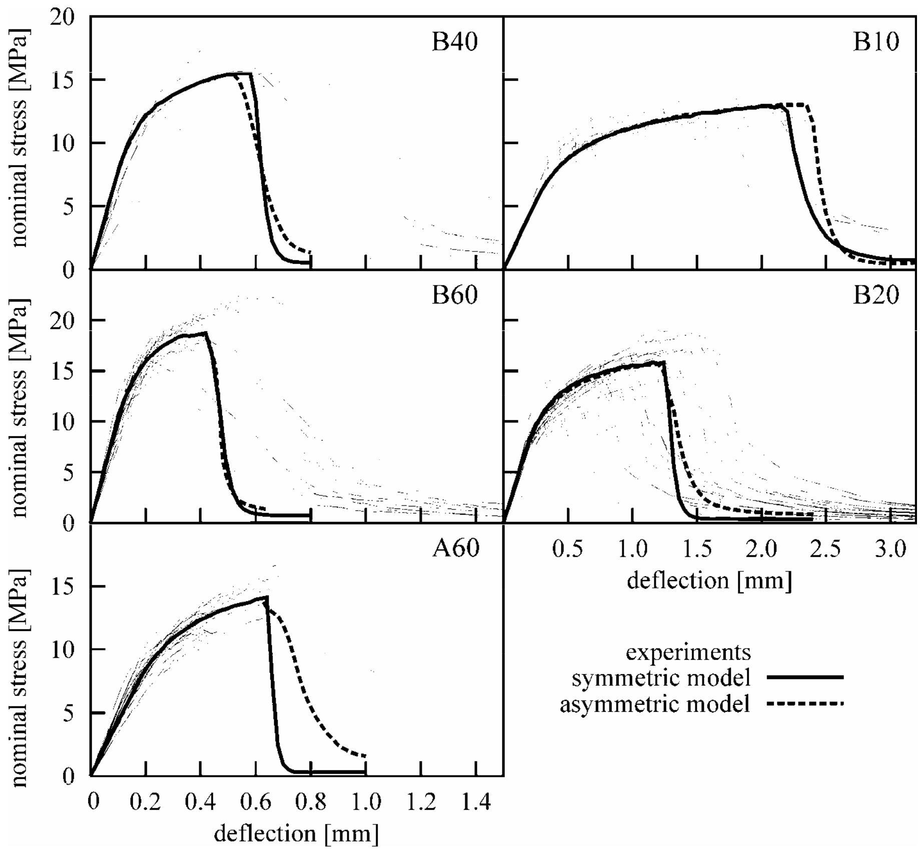

Fig. 7 Experimental responses and corresponding symmetric (asymmetric) simulation response

Figure 8 presents comparisons of experimental l-d diagrams with simulation responses. Tab. 2 summarizes the parameters used in simulations; the tensile softening was rectangular SFRC, the tensile strength of basic material f_t was always kept identical in symmetric and asymmetric cases.

		A60	B60	B40	B20	B10	
tensile strength	f_t	7.0	9.0	7.0	7.0	5.5	MPa
tensile strength of weak/strong part	$f_{t,p}$	6.0	8.0	6.0	6.0	4.5	MPa
Atena fracture energy for sym. model	G_F	25	75	50	70	60	J/m^2
Atena fracture energy for asym. model	G_F	120	200	200	210	120	J/m^2
Ratio of Atena fracture energies	r	4.8	2.7	4.0	3.0	2.0	–

Tab. 2 Parameters used for simulations plotted in fig. 8

There are huge differences of identified fracture energies G_F in symmetric and asymmetric Atena models. Their ratio r varies between 2 and 5. Since the experimentally observed failure was always asymmetric, we recommend using the asymmetric model for numerical simulations; especially when identifying material parameters of tough materials such as FRC used in our study.

5 Conclusions

The major point in the article is the need to disturb spurious symmetries in models for numerical simulations of experimental response; especially simulations targeted at inverse identification of material parameters. Numerical study documents this need using an example of four point bending beams made of FRC that were studied also experimentally. It was shown that a small disturbance of model tensile strength over a small region of a specimen may lead to quite drastic change of fracture energy needed in the model to fit the experimental data. In addition, the paper proposes an ideal shape of tensile softening needed to reinterpret experiments using simulations in Atena 2D software.

Aknowledgements

This research was conducted with the financial support of the Ministry of Education of the Czech Republic, project No. 1M06005, within activities of the CIVAK research centre.

References

[1] Červenka, V., Jendele, L., Červenka, J.: *Atena program documentation, Part 1: Theory*, 2005, Červenka Consulting, Předvoje 22, Praha, 162 00, Czech Republic

[2] Eliáš, J.: *Chování křehkých vláken v kompozitech s křehkou a kvazikřehkou matricí*, diploma thesis, Brno University of Technology, Faculty of Civil Engineering, Brno, 2006

[3] Vořechovský, M.: *Interplay of size effects in concrete specimens under tension studied via computational stochastic fracture mechanics*, International Journal of Solids and Structures **44** (9), 2715–2731, 2007, doi:10.1016/j.ijsolstr.2006.08.019

[4] Vořechovský, M. Eliáš, J.: *Modeling nonlinear mechanical response of FRC in ATENA software*, 11th International Conference Ecology and new building materials and products, June 2007, Telč