Virtual Lab for Fibre Reinforced Concrete Design by Simulation Prototyping

FibreLAB

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D3.2 FRC Parameter Optimization Software

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Project website:
http://www.fibrelab.eu

Executive summary:

This is the FibreLAB project document, which describes the software and methodology for FRC parameter optimization. This work is part of work-package W3. This document extends and replaces the previous report D3.1, and describes the available tools for the determination of FRC material parameters by inverse analysis.

The project will develop a software tool to support the design of advanced structures or products from fiber reinforced concrete (FRC) using simulation prototyping. The software will support engineers during the design process, which will be based on the simulation of the structural performance during the foreseen design scenarios for the individual design limit states: serviceability and ultimate limit states as well as the new design states such as: robustness, durability and service life verification.

The software will be developed based on the existing product ATENA developed and distributed by CER. The project will develop a separate module of this system specifically targeted for fibre reinforced concrete industry.

This product can be used separately or together with the existing ATENA software. The product shall also support parametric modelling and embedded scripting language to enable the fast development of even more specialized design tools for the development and design of specific construction products for pre-cast industry or other mass production.

Revision history:

date	author	status	changes
09.11.2018	J. Červenka	1.0	draft
18.1.2019	J. Červenka	2.0	First complete version

Table of contents:

1. General

The most critical parameter for the design or analysis of fibre reinforced concrete structures is the shape and values of the tensile softening/hardening diagram. This diagram can be given either in terms of stress-strain or stress-displacement relationship. The stress-displacement approach is a preferable one as it can properly take into account the size effect, however the stress-strain approach can be used as well if proper length scale parameter is taken into account. Such diagrams are however typically not available from the material producer. The behaviour of fibre reinforced concrete material is usually described and evaluated by experiments using four point bending experiments or three point bending tests with a notch. The true softening behaviour can be only derived by parameter identification using inverse analysis.

The objective of this work package will be to develop software tools for automated parameter identification for the FRC model to be used in the design process. The inverse analysis will be used for the parameter identification for the tensile softening/hardening law. Various approaches shall be developed and evaluated. The inverse analysis will be based either on complete mechanical model of the simulated experiment or using simplified mechanical model of the bending experiment, which consists of two elastic blocks connected with a cohesive zone representing the concrete crack with bridging forces due to the fibres. For the inverse analysis it is planned to develop an iterative stochastic optimization approach based on evolutionary algorithms.

This workpackage consists of the following tasks:

Task 3.1: Complete mechanical model for FRC identification

The complete mechanical model for the typical geometries used in FRC experiments will be developed in ATENA software and verified on selected experimental data. The complete mechanical model will use solid finite elements with the fracture-plastic based ATENA material model suitable for fibre reinforced concrete. Currently, the most suitable ATENA material is the nonlinear cementitious user material, which enables the user definition of the tensile softening/hardening curve. The parameters of the tensile diagram will be identified by the inverse analysis process developed in Task 3.3.

Task 3.2: Simplified mechanical model for FRC identification

The simplified mechanical model will be developed for the typical geometries used for fibre reinforced concrete experiment, and will be subsequently used by the inverse analysis in Task 3.3. The simplified model will consist of two elastic blocks with pre-calculated stiffness/compliance matrices and cohesive zone between them to model the crack propagation. The evolution of the bridging forces due to concrete strength and fibre contribution is modelled by cohesive law, which represents the tensile law, which needs to be identified by the inverse analysis in Task 3.3.

Task 3.3: Inverse analysis for FRC identification

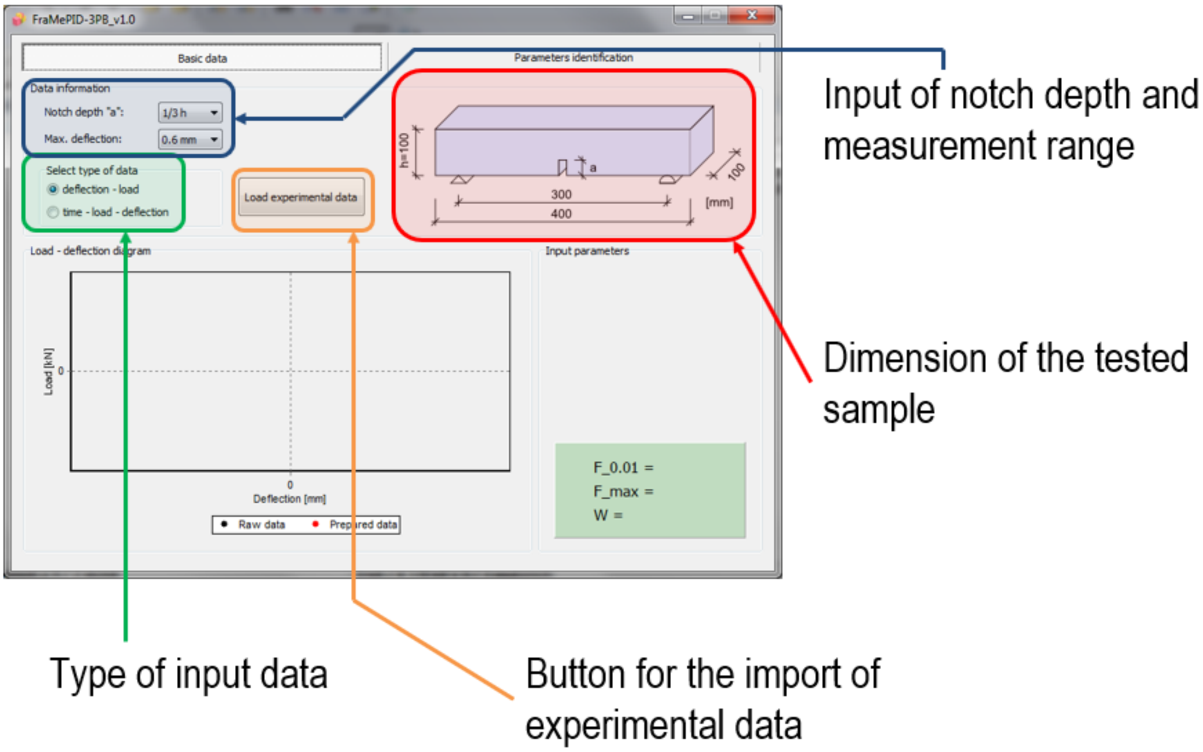
The objective of the inverse analysis is to use the mechanical models developed in Task 3.1 and 3.2 to analyse a given experiment, and determine the optimal set of material parameters that give the best fit with the measured response. This is the only reliable method how to determine the material parameters, i.e. the tensile softening/hardening law for fiber reinforced concrete to be used in the design or assessment. This is due to the fact that common standard tests are based on experiments in bending that does not directly produce the necessary parameters, so inverse analysis is necessary. The developed inverse analysis algorithm will be developed based on iterative stochastic optimization approach.

2. Software Overview

Inverse analysis for determining fibre reinforced concrete parameters can be automated by artificial neural networks. The methodology of artificial neural network based inverse analysis is general and can be used for any inverse task, which is its advantage. On the other hand it is very time consuming. In order to automate the whole difficult process of material parameters identification a FraMePID-3PB program (Figure 1) has been developed [1].

The whole system is based on standardized fracture test of beam with central edge notch in three-point bending according to the RILEM Technical Recommendations [2]. The finite element computational model implemented in FraMePID-3PB is created in ATENA software (described e.g. in [3]). The "3D Nonlinear Cementitious 2" material model for concrete is used. For modelling of tensile softening the exponential function according to [4] has been used.

Previous identifications using various types of concrete mixtures and ages showed that the structure of artificial neural network used for identification in this testing configuration is in all cases almost the same. Thank to that and using standardized test the time needed for inverse analysis can be significantly reduced because only one neural network is created, trained, tested and implemented within FraMePID-3PB system. Therefore, time consuming training set preparation using stochastic nonlinear analysis and training of the network using suitable optimization technique is performed only once. Structure of neural network implemented within FraMePID-3PB system is as follows (see Figure 2): 1 hidden layer with 5 nonlinear neurons (hyperbolic tangent transfer function), output layer with 3 linear neurons (linear transfer function) and 3 inputs of the network.

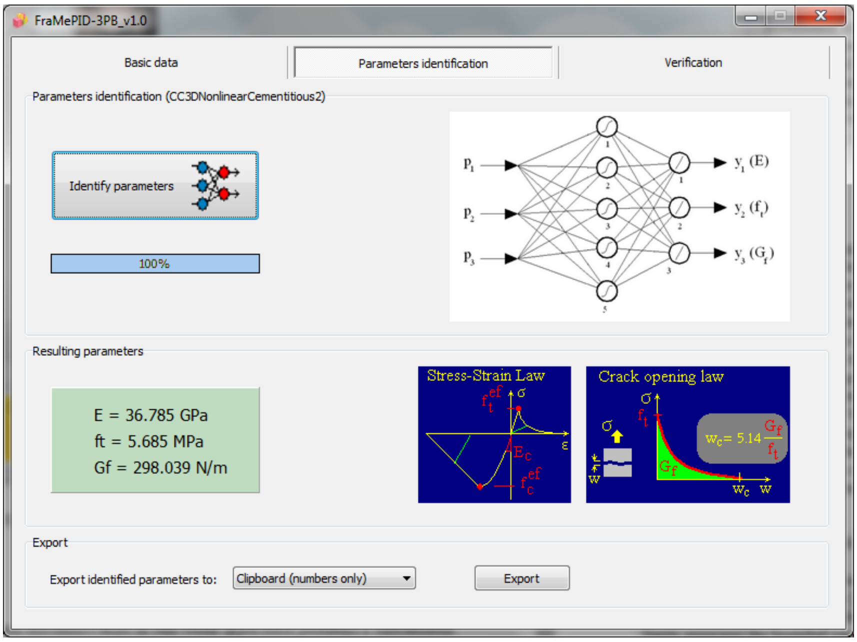


Notch depth "a": 1/3 h
Max. deflection: 0.6 mm

Select type of data
● deflection - load
○ time - load - deflection

F_0.01 =
F_max =
W =

Figure 1: FraMePID-3PB tool panel – experimental data loading and preparation of input signal for neural network



E = 36.785 GPa
ft = 5.685 MPa
Gf = 298.039 N/m

Export identified parameters to: Clipboard (numbers only)

Figure 2: FraMePID-3PB tool panel – structure of neural network and material parameters identification

Three output neurons correspond to three material parameters which are being identified (modulus of elasticity, tensile strength and specific fracture energy), three inputs correspond to three parameters extracted from L–D diagram.

During training set preparation for artificial neural network material parameters are randomized. Here, purposely large variability was used in order to create rather general network which will be able to identify parameters of concretes of various strengths and ages. The demonstration example presented here represents a standard concrete type: mean values are 40 GPa for modulus of elasticity, 4.5 MPa for tensile strength and 200 J/m^2 for fracture energy. Coefficients of variation are 0.2 for modulus of elasticity, 0.25 for tensile strength and 0.4 for fracture energy. Training set was generated using 100 simulations of Latin Hypercube Sampling method. Training of the network was carried out using Levenberg–Marquardt [5] and genetic algorithms [6] optimization methods.

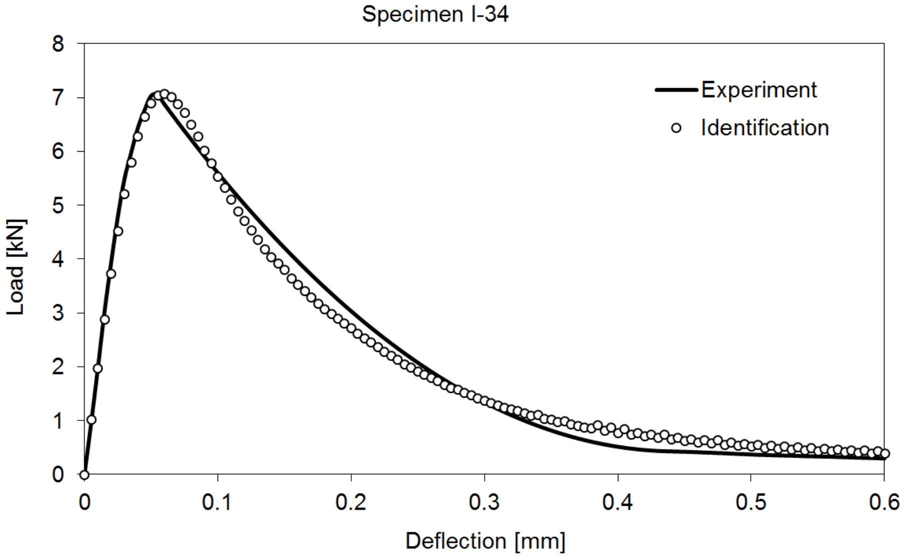


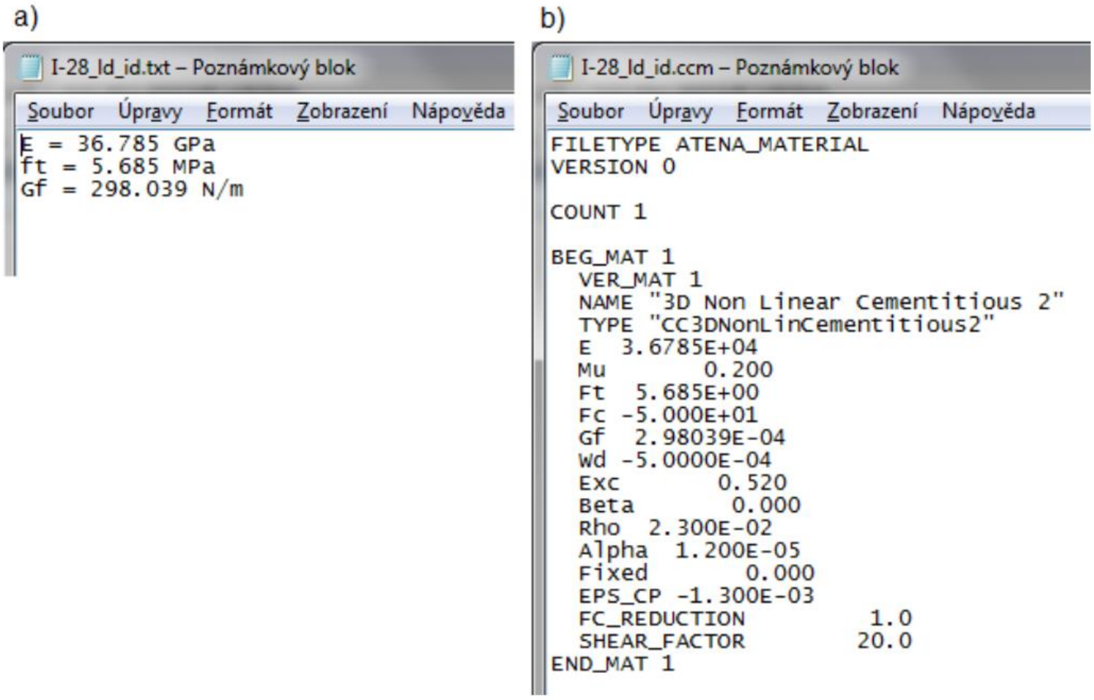
Figure 3: Comparison of selected experimental and numerically simulated load–deflection diagrams with material parameters obtained from identification

The procedure of material parameters identification using FraMePID-3PB tool can be itemized as follows:

I. L–D diagram obtained from experiment is loaded into FraMePID-3PB. Curve is analysed and inputs of inverse analysis are extracted and prepared for neural network (Figure 1).
II. Input signal is transmitted through the neural network and from the output layer of the network the best set of material parameters is obtained. This step is possible because neural network is trained in advance and remains the same for parameters identification of various concretes (Figure 2). Emphasize, that there is no new nonlinear fracture mechanics calculations to train network – the network is ready to use and implemented in FraMePID-3PB.
III. Verification of identification is performed. Obtained material parameters are used in the computational model and numerical analysis is carried out. Here, ATENA software is linked to FraMePID-3PB for data transfer. Resulting L–D diagram is compared with experimental one which will show to what extent the inverse analysis was successful (Figure 3).

The FraMePID-3PB software operates recently with "basic" configuration of experiment and model of standard concrete as demonstrated in the above example, but it is designed more generally with respect to next future extension for other configurations, e.g. specimens with various notch depths, other softening models of concrete (linear, multi-linear, etc.), additional testing configurations (compressive test, wedge splitting test), etc. This will help with routine material parameters identification for various research and practical tasks.

From the inverse analysis it is possible to conclude recommended values of mechanical–fracture parameters for deterministic and stochastic nonlinear FEM analyses of beam/structures made of the analysed concrete. Two-parametric lognormal probability distribution function can be suggested for the identified parameters (modulus of elasticity, tensile strength and fracture energy) based on curve fitting tests carried out using FReET stochastic software [7] and JCSS Probabilistic Model Code recommendations [8]. Further results from the demonstration example can be found in [9], another results based on this methodology including practical applications were presented in [10], [11] and [12].



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E = 36.785 GPa
ft = 5.685 MPa
Gf = 298.039 N/m
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VERSION 0

COUNT 1

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  TYPE "CC3DNonLinCementitious2"
  E  3.6785E+04
  Mu        0.200
  Ft  5.685E+00
  Fc -5.000E+01
  Gf  2.98039E-04
  Wd -5.0000E-04
  Exc         0.520
  Beta        0.000
  Rho  2.300E-02
  Alpha  1.200E-05
  Fixed       0.000
  EPS_CP -1.300E-03
  FC_REDUCTION         1.0
  SHEAR_FACTOR        20.0
END_MAT 1
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Figure 4: Examples of data exported to: a) text file, b) file .ccm

3. Approaches for Material Parameter Optimization

Determination of appropriate material parameters for the fibre reinforced concrete material model [13] in design and assessment of structures is an important task, which is necessary for realistic modelling of FRC structures.

There are many guidelines to model and design fibre reinforced concrete, such as RILEM TC162-TDF [14], *fib* Model Code 2010 [16], ÖVBB Richtlinie Faserbeton [17], ACI 544.8R-16 [18], CNR DT [19]. All of these guidelines are based on a three or four point bending tests. Obtained test results as load-displacement or load-CMOD diagrams are converted to the parameters that can be used as a material model. RILEM and *fib* Model Code 2010 use residual strengths and define "stress-crack width" or "stress-strain" diagrams that can be applied as material laws. ACI describes an indirect method to obtain the stress-strain response.

In finite element model the stress-strain diagram can be used if the characteristic length and the direction of the principal stress is known. In this case, the stress-strain can be converted to stress-crack width and the crack localization can be handled. For this purpose, the crack band size method can be used [3].

These stress-strain models based on guidelines can be applied if the Bernoulli-Navier hypothesis is valid (and as a consequence there is a linear elastic stress distribution in the cross section). However, in reality, the stress distribution will be different due to the notch that is usually in the middle of the specimen for three point bending test or due to the cracks in the material that are formed during the test.

In this case, it is necessary to obtain material laws for finite element analysis by different method. As was shown in papers [10], [20] material parameters can be determined by inverse analysis of results from basic tests as three of four point bending. Another method was proposed by Juhász [21] and it works with fracture energy of material composed of concrete matrix and fibres. It is reasonable to model the FRC with "stress-crack width", instead of "stress-strain" diagram. The shape of the softening curve after post crack can depend on the type of the fibre and the dosage, but most of the time it can be simplified as a constant value after crack (so called residual strength). The area under the "stress-crack width" diagram is the fracture energy. This fracture energy could be divided into 2 parts: fracture energy of the concrete matrix G_F and added fracture energy of fibres G_{Ff}, see Figure 5. These two methods are discussed in this chapter and compared with material laws obtained by guidelines.

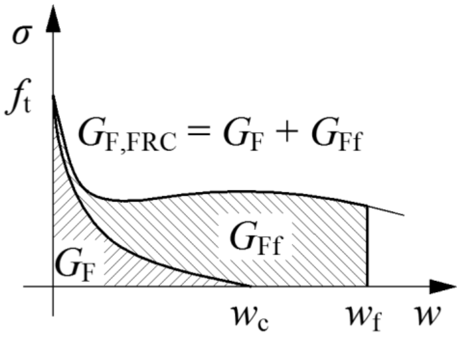
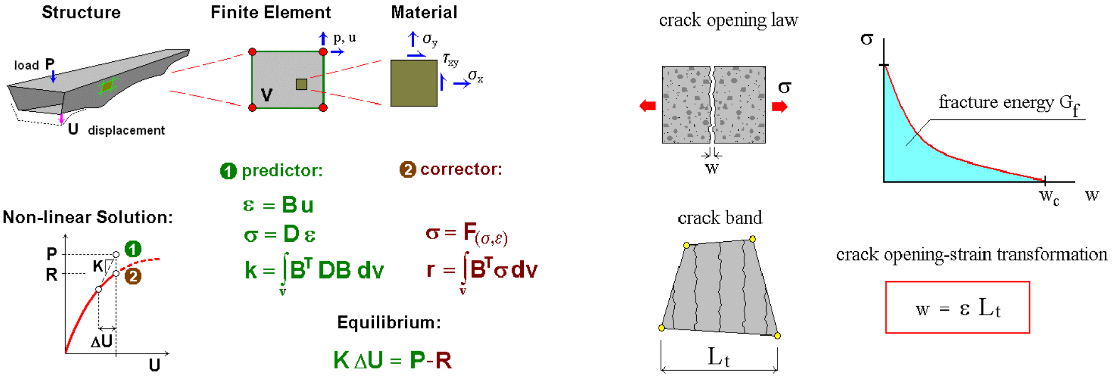


Figure 5: Fracture energy of the concrete and added fracture energy by the fibres

3.1 Finite Element Analysis

Behaviour of FRC material is analysed in program ATENA [22] for non-linear analysis of concrete structures. ATENA is capable of a realistic simulation of concrete behaviour in the entire loading range with ductile as well as brittle failure modes as shown for instance in [23]. It is based on the finite element method and non-linear material models for concrete, reinforcement and their interaction. The tensile behaviour of concrete is described by smeared cracks, crack band and fracture energy and the compressive behaviour of concrete by a plasticity model with hardening and softening. The constitutive model is described in detail in [24]. Nonlinear solution is performed incrementally with equilibrium iterations in each load step.

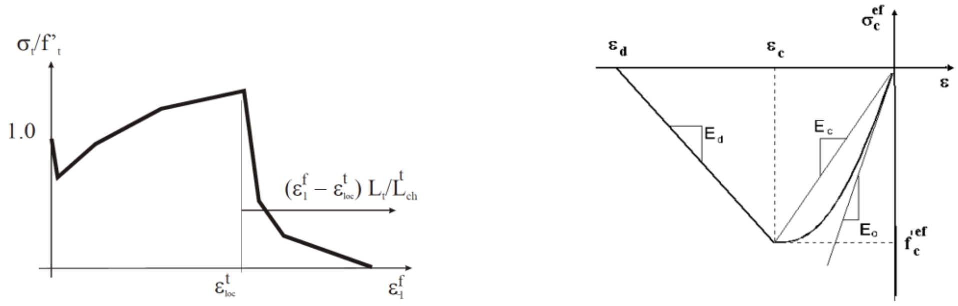


(a) (b)

Figure 6: (a) Scheme of the nonlinear finite element method, (b) smeared crack model for tensile behaviour of concrete

3.1.1 FRC Material Models

The tensile response of FRC differs from normal concrete not only in the values like tensile strength and especially fracture energy, but also in the shape of tensile softening branch. The original exponential function valid for normal concrete can be used as a first approach, but preferably would be to use more realistic form of the tensile constitutive law. Therefore, special material models at macroscopic level are needed for modelling of fibre reinforced concrete.



(a) (b)

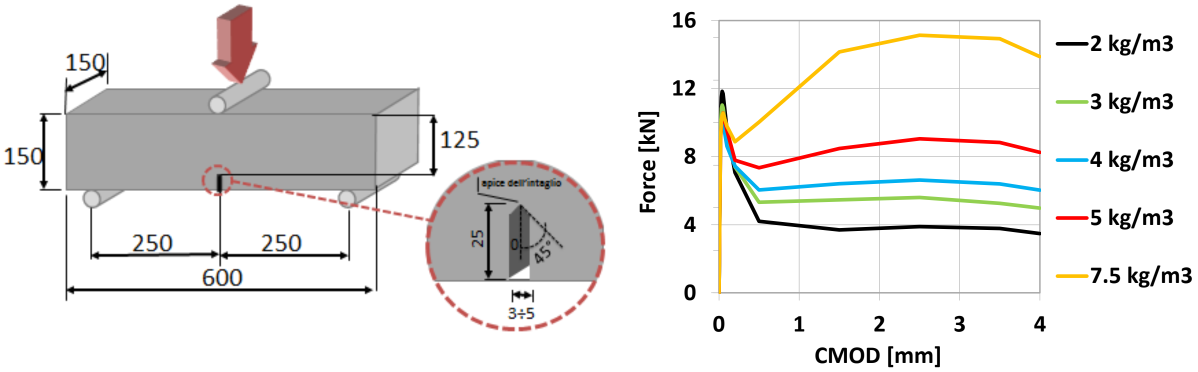
Figure 7: (a) User defined tensile behaviour, (b) compressive stress-strain law

The most sophisticated and most general model of FRC material represents an extension to the fracture-plastic constitutive law [24] called 3D NLC2 User model. It describes the tensile behaviour according to the material response measured in tests point-wise in terms of the stress-strain relationship. The first part of the diagram is the usual stress-strain constitutive law. After exceeding the localization strain ε_{loc} the material law assumed for the characteristic crack band width L_{ch} is adjusted to the actual crack band width L_t. The characteristic crack band width (characteristic length) is the size (length) for which the defined material law is valid. The same procedure (with eventually different characteristic length) is used for the compression part of the material law. Compressive stress-strain law of mentioned material models is described in Figure 7. The softening law in compression is linearly descending and the end point of the softening curve is defined by plastic displacement w_d (corresponding to ε_d in Figure 3b). By increasing material parameter w_d the contribution of the fibres to the compressive behaviour of concrete is considered. Another important compressive parameter for FRC modelling is reduction of compressive strength due to cracks which says how the strength is reduced while the material is subjected to lateral tension.

3.2 Experimental Program

Experimental program focused on application of synthetic fibres called BarChip48 in concrete C25/30 is chosen for the presented study. Different dosages of fibres were tested as is shown in load-displacement diagrams in Figure 8b. Six tests were provided for each dosage, the plotted curves represent mean values. Geometry of the specimen and test setup corresponds to EN 14651 [25]. Beams were tested under three point bending condition. The cross section is 150x150 mm and span is 500 mm. The central part of the beam is weakened by notch 25 mm long, see Figure 8a.

Result for fibre dosage 2 kg/m^3 was chosen for numerical analysis presented in this chapter.



(a) (b)

Figure 8: (a) Geometry of tested specimen, (b) comparison of LD diagrams for different fibre dosages

3.3 Material Law for Fibre Reinforced Concrete

3.3.1 Recommendations from Guidelines

As a representative document, RILEM TC162-TDF is chosen for determination of the material law. Experimental programme described in previous chapter involves the same test procedure and specimen geometry that is described in RILEM. Flexural tensile strengths $f_{R,i}$ are determined Based on Bernoulli-Navier hypothesis by expression:

$$f_{R,i} = \frac{3F_{R,i}L}{2bh_{sp}^2} \tag{1}$$

where *b* is width of the specimen,
h_{sp} is distance between tip of the notch and top of cross section,
L is span of the specimen,
$F_{R,i}$ is load recorded at CMOD_i.

Maximal flexural strength $f_{fctm,fl}$ and residual flexural strengths for crack mouth opening displacement *CMOD* 0.5 mm ($f_{R,1}$) and 3.5 mm ($f_{R,4}$) are used for the determination of material law, see Figure 9 left. Stress-strain diagram defined by RILEM is trilinear, for the numerical model part after the peak is important. Final diagram utilized in the numerical analysis contains bilinear softening as is shown in Figure 9 right.

The finite element model for bending test is made for a plane stress simplification, with low order quadrilateral elements with 2x2 integration scheme, with the square elements shape and size of 5 mm, i.e. 30 elements through the height (25 elements above notch), see Figure 10a. The loading is applied by force on the top loading plate. *CMOD* is calculated as difference between horizontal displacement of the right and left bottom part of the notch. Characteristic length for tensile stress-strain diagram is equal to the element size, i.e. 5 mm.

Comparison of the load-displacement diagram from test and numerical simulation is shown in Figure 10b. Model can correctly describe behavior on the tail of the diagram but there are differences after the crack localization. Model according to RILEM underestimate the flexural strength of the material.

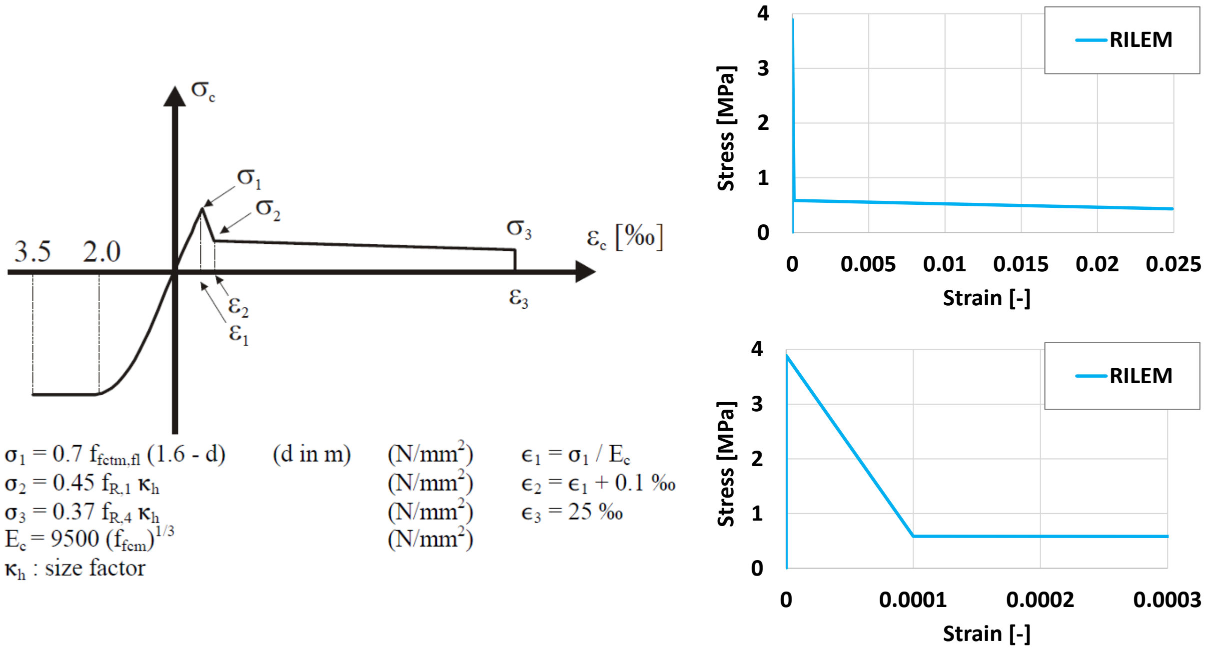
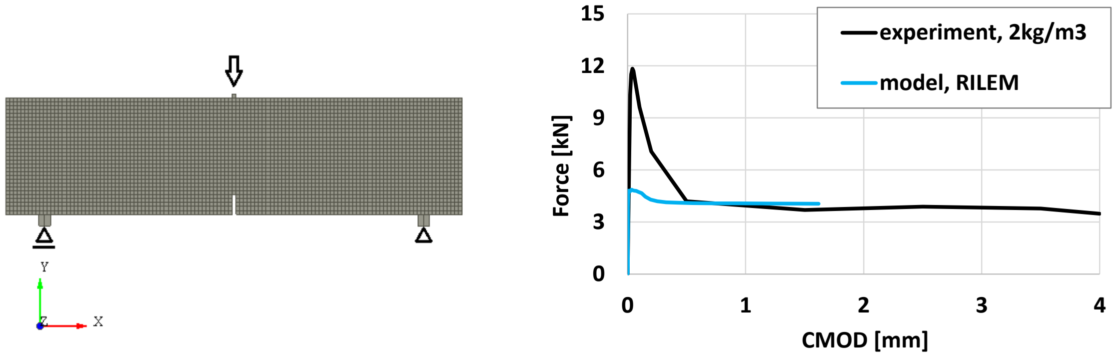


Figure 9: (left) Stress-strain diagram according to RILEM TC162-TDF [14], (right top) diagram for material with fibre dosage 2 kg/m³, (right bottom) detail of the diagram until strain 0.0003



(a) (b)

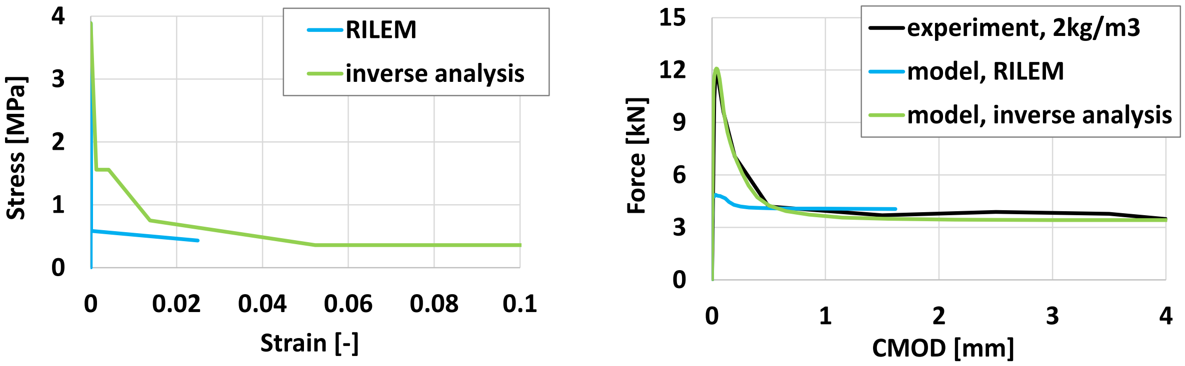
Figure 10: (a) FEM model of three point bending test, (b) comparison of experimental result for fibre dosage 2 kg/m^3 and model with RILEM material law (characteristic length 5 mm)

3.3.2 Inverse Analysis

Another way how to obtain FRC material law for nonlinear finite element analysis is inverse analysis of experimental results which consists of two main steps. The first one is the estimation of material law based on mixture, contents and type of fibres, etc. or guidelines recommendations. The second step is modification of initial law by inverse analysis of material tests, mainly four-point bending test until the required accuracy of results is achieved.

In this case, RILEM material law was utilized as an initial function and by several simulations it was modified to the optimal material law for investigated FRC that is shown in Figure 11a. It is obvious that material law is described in more detail compared to the RILEM and it leads to more accurate behaviour during bending test, see Figure 11b.

Advantage of this approach is that it can be used for any experimental result and specimen geometry and it is possible to describe material very precisely. As a disadvantage, more than one numerical simulation are necessary for satisfactory result. For example, presented result was found by performing three analyses. For automated inverse analysis, it is possible to use program FraMePID-3PB presented in chapter 2.



(a) (b)

Figure 11: (a) Stress-strain from inverse analysis in comparison with RILEM, (b) comparison of experimental result for fibre dosage 2 kg/m^3 and model with RILEM material law and law obtained by inverse analysis

3.3.3 Modified Fracture Energy Method

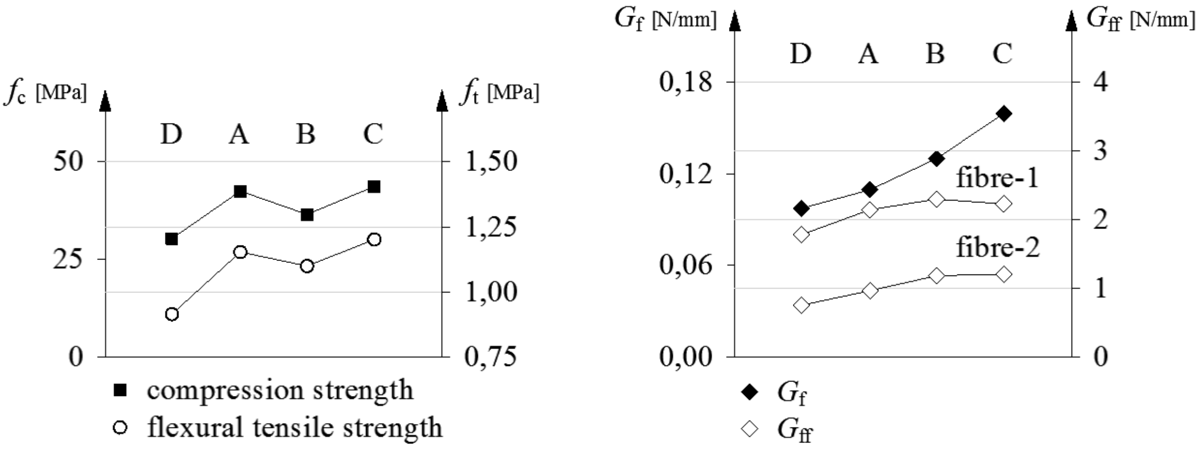
The third method was proposed by Juhász [21] and it utilizes the fracture energy of the FRC.

A thin band with micro-cracks will appear due to the tensile stress in the concrete – which is called the crack process zone. By increasing the stress the concrete reaches its tensile strength when the micro cracks are touching each other. After this point the tensile capacity of the concrete will decrease, the cracks will bypass or cross the aggregates and then the entire section will be crossed by the crack. The area under the "tensile stress – crack width" diagram is the fracture energy.

The fracture energy of the concrete is influenced by a number of factors which are clearly not related to the concrete's strength class. Most of the existing design methods neglect the fracture energy of the concrete and do not pay much attention to the tensile strength. However, when designing FRC structures these parameters cannot be ignored.

The main goal in this method is to separate the fracture energy of the concrete (G_F) and added fracture energy by the fibres (G_{Ff}). According to previous research [26], the added fracture energy depends on the fibre type, dosage and cement mortar (cement, water and sand). By knowing these values the added fracture energy could be defined and used as a parameter partly independent from the concrete. In this research, concrete with the same cement mortar but with different aggregate type and size was made. In the case of normal aggregate (type *A*, *B* and *C*) the added fracture energy (G_{Ff}) was mostly unchanged.

Application of this method in the numerical modelling to compare result with methods mentioned in the previous chapters will be provided during the further research.



(a) (b)

Figure 12: (a) Compression strength and flexural tensile strength of concrete A, B, C and D, (b) fracture energy of the concrete A, B, C, D and added fracture energy of fibre-1 and fibre-2

4. Examples

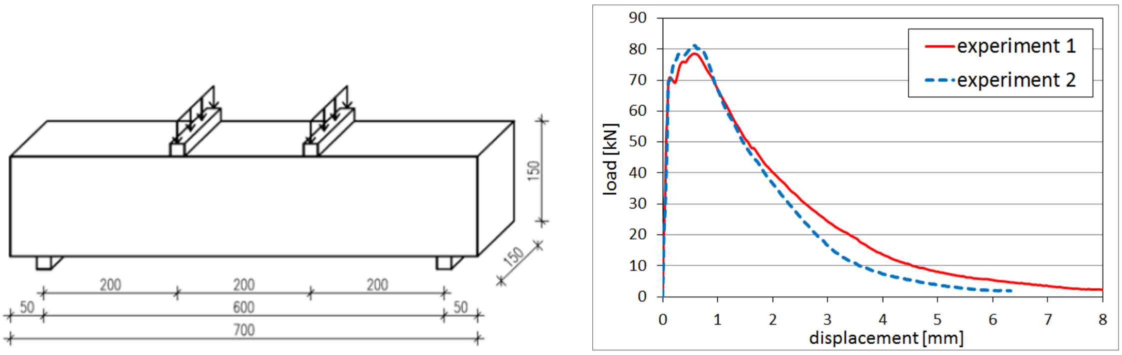
4.1 Layered FRC Structural Elements

As an example of procedure of FRC modelling by nonlinear finite element method, layered FRC elements were chosen [27]. Layered FRC elements are created from two or more layers of material with continuously variable composition and microstructure. Since the fibres are one of the most expensive components of the composite the aim is to use them as efficiently as possible and thereby reduce the amount of fibres and cost of materials at the same time. The principle consists in gradually changing the material composition and microstructure over a structural element volume so that the local properties meet the local load-resisting requirements.

The layered structural elements can be used for façade panels, floor structures in buildings (for new buildings as well as for reconstruction), for bridge structures or impact and blast resistant elements. In this chapter, the layered element consisting of five layers and designed to sustain bending moment is presented.

4.1.1 Identification of FRC Parameters

The FRC input parameters must be determined for material corresponding to the class C110/130. Concrete matrix is reinforced with the steel fibres in volume fraction 1.5 %. Experimental verification of cylinder compressive strength after 28 days is 125 MPa, Young's modulus is 45 GPa. Identification of FRC parameters is based on the results of four-point bending tests, see Figure 13.

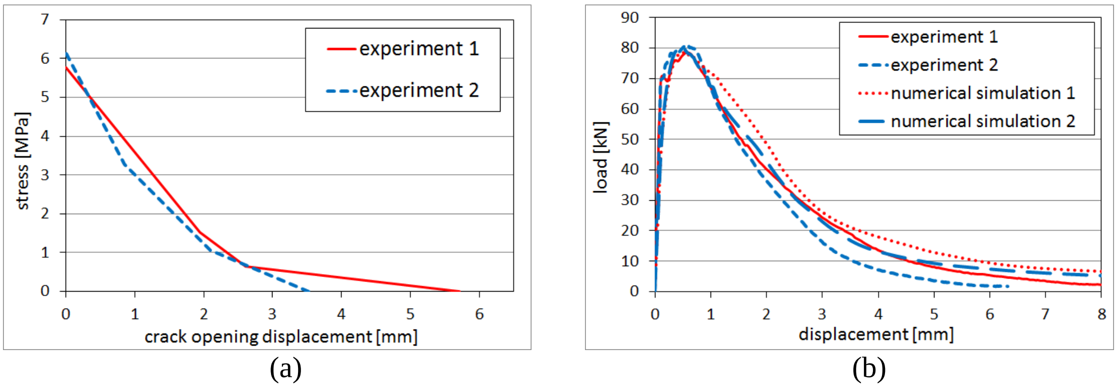


(a) (b)

Figure 13: (a) Scheme of four-point bending test, (b) Experimental results

For the inverse analysis, stochastic approach can be used (randomization of initial material input parameters by probabilistic system SARA, numerical reproduction of four-point bending tests, comparison with experimental results and selection of appropriate parameters). Another approach is software Consoft developed by prof. Dr.-Ing. Volker Slowik and his colleagues at the University of Applied Sciences in Leipzig, Germany [28]. Automatic analysis based on the evolutionary algorithms is used for the determination of cohesive law function. The second approach was applied in this study.

The best results of inverse analysis are shown in Figure 14. Softening curves for two material models are shown in the Figure 14 (a), comparison between numerical and experimental results is shown in the Figure 14 (b). The results of numerical simulations are in a perfect accordance with the experimental results.

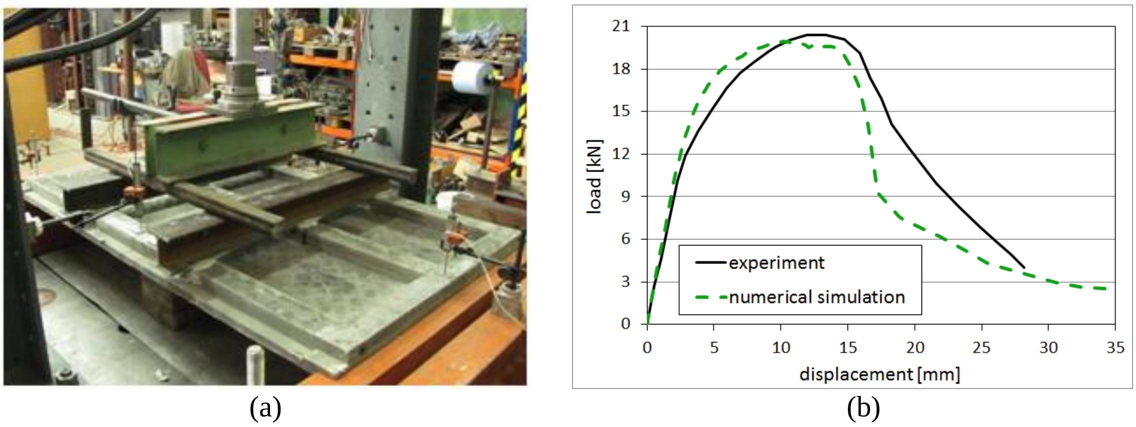


(a) (b)

Figure 14: (a) Softening curves, (b) Comparison of experimental results and numerical simulations of four-point bending tests

4.1.2 Validation of Modified Material Model

Material model 3D NLC2 User with softening curve derived in the previous chapter was validated by the numerical simulation of bridge slabs used for reconstruction of a bridge in Czech Republic; they should serve as a permanent formwork [29]. Slabs are made from the same material as was described in the previous chapter. Four-point bending tests of these slabs were carried out as shown in Figure 15 (a) – photo from the lab of the Klokner Institute of CTU. The dimensions of the slab are 1 x 1.67 m, the thickness is 20 mm, the rib thickness is 60 mm and thickness of the central rib is 40 mm. Load bearing capacity of the model was 20.6 kN which is pretty close to the experiment. The failure (fracture) of the slab occurred also in accordance with the experiment in the transverse direction approximately at the edge of loading plate.



(a) (b)

Figure 15: (a) Four-point bending test of slab, (b) Comparison of experimental and numerical results

4.1.3 Numerical Simulation of Layered FRC Element

Layered beam designed to sustain bending moment consists of five layers whose fibre volume fraction increases linearly from the upper surface toward the bottom. Fibre volume fractions of all layers are depicted in Figure 16. Total volume fraction is identical with the homogenous beam from the previous chapter, i.e. 1.5 %. Based on the cohesive law for fibre volume fraction 1.5 % derived by inverse analysis, softening curves for other layers are determined by micromechanical model presented in [30], see Figure 17 (a).

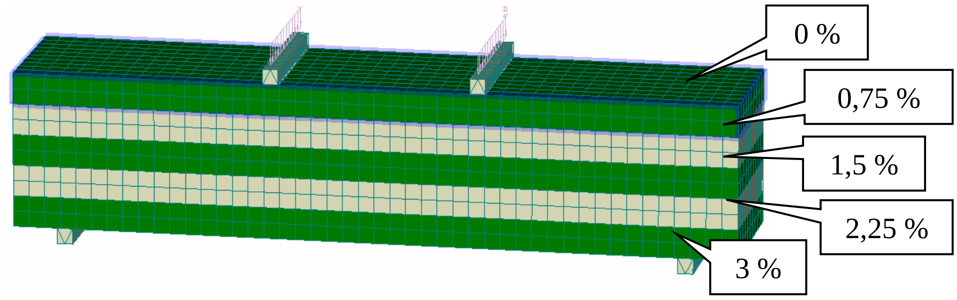
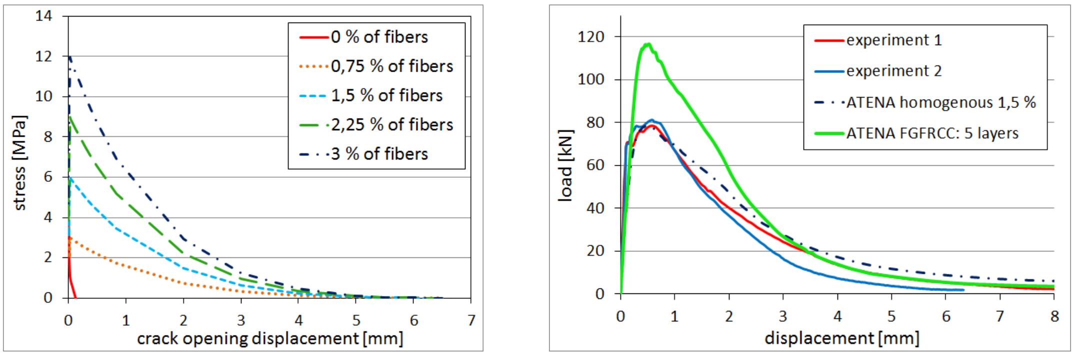


Figure 16: Layered structural element – fibre volume fraction of layers

The spatial variability of mechanical properties was modelled by division of the structural member into macroelements representing different layers of layered member. Each macroelement has specific material model with different fibre volume fraction. Macroelements are connected with each other by an interface with the same properties as the material of macroelements.



(a) (b)

Figure 17: (a) Softening curves for different fibre volume fraction, (b) Comparison of layered and homogeneous beams

Load-displacement diagram of the layered model is shown in Figure 17 (b) in comparison to the homogenous beam with fibre volume fraction of 1.5 %. The comparison of the curves shows that the layered beam achieves 46% higher load bearing capacity (117 kN compared to 80 kN). Comparison of crack width in the results of numerical analysis is also an important criterion for quality evaluation - at the load of 80 kN maximum crack width in homogenous beam is 0.25 mm while for layered beam it is only 0.012 mm, see Figure 18.

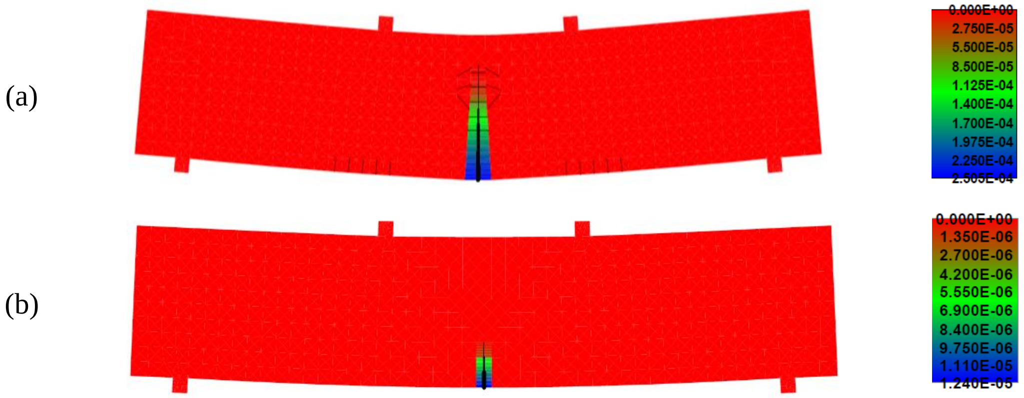


Figure 18: Cracks in beam for load 80 kN – (a) Homogeneous beam, (b) Layered beam

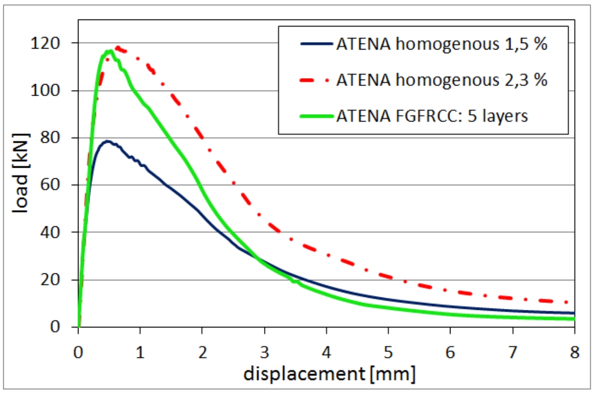


Figure 19: Comparison of homogeneous and layered beams

The results show that the proper arrangement of layers can increase the load bearing capacity by 45 % at the same total quantity of steel fibres. In this specific case, the load bearing capacity of layered element (with a total fibre volume fraction of 1.5 %) is comparable with the load bearing capacity of homogenous element with 2.3 % fibres by volume, see Figure 19. By the nonlinear numerical analysis is shown that it is possible to save 35 % of fibres and still achieve the same load bearing capacity.

The nonlinear finite element modelling can be successfully used for analysis of behaviour and failure of FRC structures. Crack initiation and development, load carrying capacity and post-critical behaviour of the structures, structural parts or experimental specimens can be investigated. Advanced material models for numerical simulation of fibre reinforced concrete are available. Determination of appropriate material parameters for model is of crucial importance. As shown in this chapter, the required values can be efficiently determined using inverse analysis of basic experiments as four-point bending test.

4.2 Design of SFRC segments by nonlinear analysis

The example deals with a design of precast tunnel segments made from steel fibre reinforced concrete (SFRC) used for Ejpovice railway tunnels in the Czech Republic. Recent possibilities of the non-linear finite element analysis (NLFEA) offer a versatile tool for design of SFRC structures. For the modeling of the SFRC material special numerical models are available accounting for the SFRC specifics such as shape of tensile softening branch, high toughness and ductility. Appropriate input material parameters can be identified from the measured response of material bending and compressive material tests using inverse analysis procedure. Obtaining suitable input material parameters of these model is not a simple task since they are not always represented by directly measurable physical characteristics of the construction material. However, they can be determined by inverse analysis of the measured response of the SFRC structural element, e.g. beam in four point bending test. Combination of nonlinear numerical simulation and laboratory tests of precast tunnel segments is used to assess tunnel lining. Numerical analysis and structural design of the segments for TBM technology are performed for various construction phases and loading scenarios. Design and assessment of segmental lining consist of the following analyses:

- Inverse analysis of tests – determination of material characteristics
- Model of segment in compression (construction phase – segment fixing - keystone A)
- Design and evaluation of SFRC segmental lining
- Assessment of the load cases: demoulding, handling and storage of segments

The results of numerical simulations are compared with laboratory tests during preparation of the project and construction design. The response of structural elements at operating load and damage at ultimate load are evaluated in order to verify and support possibility of assessing SFRC segments by methods based on nonlinear finite element analysis.

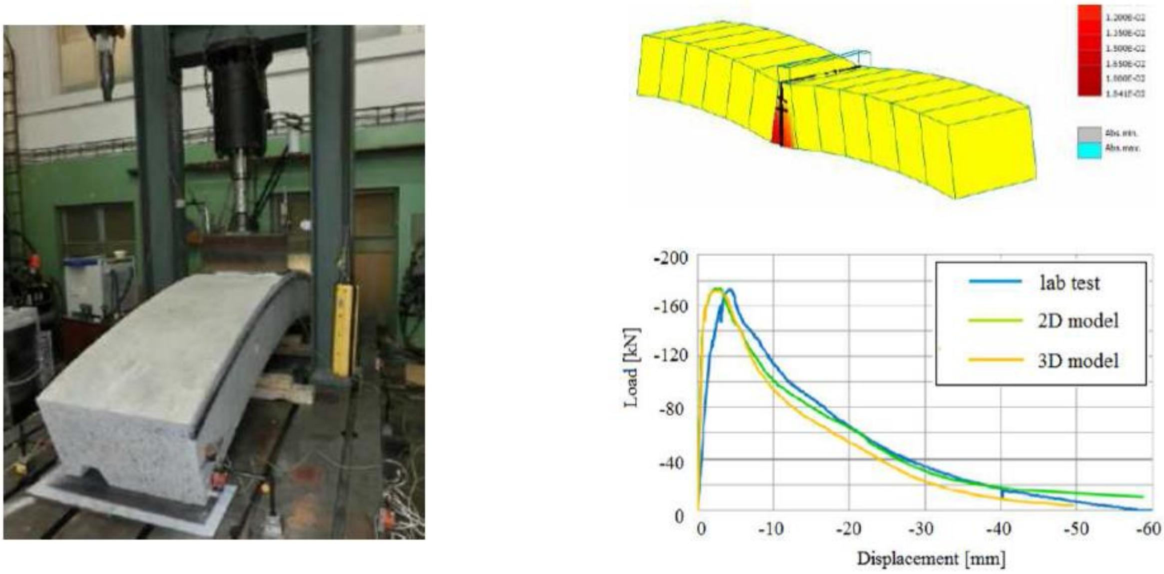


Figure 20: Identification of material parameters for SFRC model – bending test in lab (left), failure of numerical model (top right), load-displacement diagram of test and models (bottom right)

Bending tests of SFRC precast segment performed by Klokner Institute in Prague (Vokáč, Bouška [15], Figure 20, left) are used for identification of material parameters which are necessary as an input for the nonlinear material model in ATENA software. The appropriate material parameters are determined by inverse analysis of load displacement curve (Figure 20, right) and failure mode of test and model. The methodology and procedure for identification of appropriate parameters of the SFRC material model is described in [20] and [31] in more detail.

Material parameters obtained by inverse analysis are verified by analysis of keystone A which was subjected to compression test in the Klokner Institute (Vokáč, Bouška [15]). The keystone was loaded by concentrated pressure in the central part (see Figure 21) according to the conditions during installation of segments by TBM. Comparison of results and failure modes between the laboratory test and the model (Figure 21) confirmed that the identified model is well suitable for modeling SFRC structures.

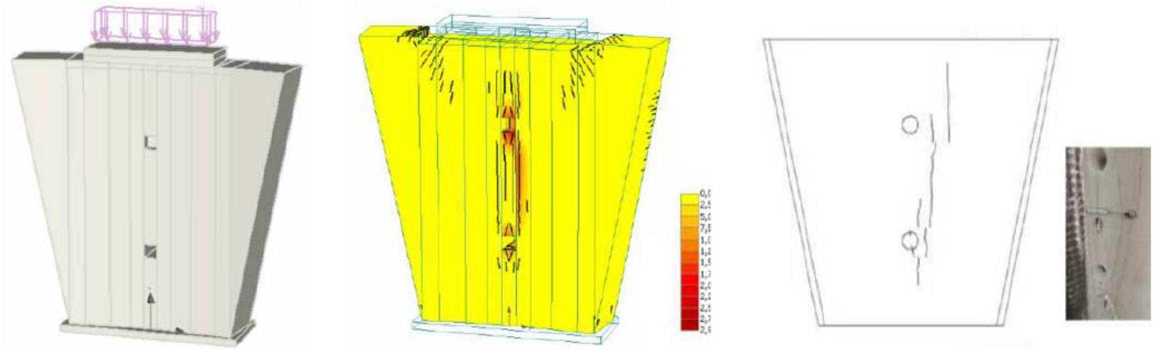


Figure 21: Model of keystone, crack pattern in the model and results of laboratory test

ATENA software was used for design and assessment of SFRCtunnel lining as well as for identification of material parameters. Segmental lining wasassessed in four cross sections of Homolka massif and Chlum massif. Nonlinear material models considering all relevant aspects of concrete behavior in compression and tension were utilized for a realistic simulation of concrete structures. The tensile cracks are modeled by smeared crack concept with strain localization in continuous material. Crack formation is controlled by nonlinear fracture mechanics with softening characterized by fracture energy (Juhasz 2013 [21]) and tensile stress-strain curve. Fracture-plastic material model [22] in plane stress state is applied in the model of tunnel lining section 2 meters long. Model was divided into finite elements of edge length 0.06 m. The whole model consists of 2892 finite elements with 56 nodes. Load in each load step increase gradually by Newton-Raphson method with convergency accelerator (Line Search).

The contact no-tension finite elements are considered in the model between individual segments. Contact material describes the physical properties of contact between two surfaces.

Geotechnical parameters used in the model are based on the values obtained from geological survey. The following load cases were considered in the simulations:

- Structure self-weight
- Temperature increase – summer (S)
- Temperature decrease – winter (W)
- Multipurpose vehicle (M) – load during construction process
- Ganter (G) - load during construction process
- Rock pressure (RP)

- Water (W)

The state of non-uniform temperature increase and decrease was also taken into account in the combination of load cases. The intensity of this state depends on distance between monitored section and portal and on the year season. Loading by water column was determined from geological survey sources. This load is considered was a continuous trapezoidal around the structure perimeter. Expected rock pressure for mined part of Ejpovice tunnels was determined by geotechnical finite element calculations. Short-term loading during the tunnel construction is also considered in calculation, it includes for example weight of the multipurpose vehicle.

Crack width, strain, limitation of compressive stress and ovalization of the tunnel l (Ejpovice) were assessed within the serviceability limit state, the. The SLS was evaluated for unreinforced segmental lining in all sections during relevant load cycles. Opening of insulation frames was observed at the contact gaps. From the evaluation of the ovalization the worst load case combination for the segmental lining was determined. Waterproof insulation is validated according to producer of the insulation parts.

The relative displacement in the contact between segments was modeled by contact elements. Contact model is based on a dry friction model (Mohr-Coulomb) defined by shear cohesion and coefficient characterizing the angle of internal friction. Figure 22 shows displacement of contact elements in the model under loading.

In the ultimate limit state the structure was subjected to the above mentioned load cases and their combinations. The design material parameters of SFRC were used for calculations.

The most unfavorable load combination except the installation load (pressure of jacks) is rock pressure combined with water column in winter season. The cross section subjected to these critical combination is assessed in compression and bending including check of the shear forces.

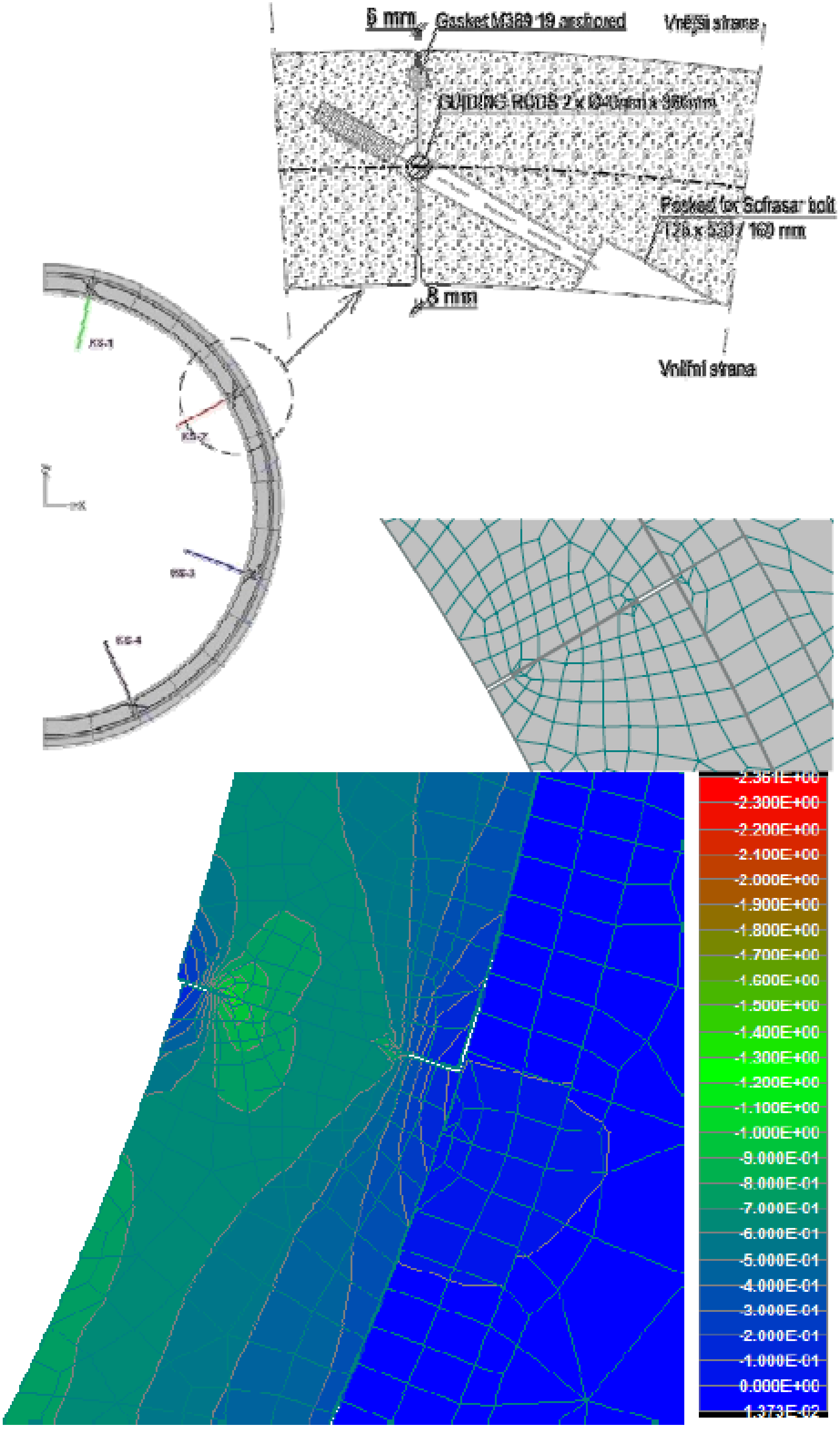


Figure 22: Contact detai (left), contact displacement in ATENA model (right)

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