IDENTIFICATION OF MATERIAL PARAMETERS FOR NONLINEAR MODELING OF FIBRE REINFORCED CONCRETE STRUCTURES

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Abstract

The nonlinear finite element modelling can be successfully used for analysis of behaviour and failure of fibre reinforced concrete (FRC) structures. Crack initiation and development, load carrying capacity and post-critical behaviour of the structures, structural parts or experimental specimens can be investigated. Nonlinear fracture analysis accounting tensile capacity of material enables to exploit reserves, which are usually neglected or diminished in codes or in the linear analysis. Since the tensile behaviour in the FRC is dominating, the potential profit from the nonlinear analysis of FRC-based structures is much higher than in standard reinforced concrete structures. Special constitutive material models were developed for description of tensile properties of the FRC-material in the nonlinear finite element analysis. They account the high toughness and ductility of FRC as well as possible uncertainties and spatial variability of the material properties. Input material parameters for the numerical models and their practical utilization are here of crucial importance. An extensive inverse analysis of different types of FRC material tests has been performed and evaluated. Based on the obtained results the optimal material input sets for practical utilization of the different numerical material models of FRC were suggested and applied in design practise.

Keywords: computer simulation, fibre reinforced concrete, nonlinear material models, identification of material parameters, fracture analysis

1. Introduction

The nonlinear finite element simulation is recently a well-established approach for analysis of reinforced concrete structures and it has a big potential also in the field of fibre reinforced (FRC) structures. Special material models at macroscopic level are available for modelling of FRC-material in the numerical simulation of FRC-based structures. Appropriate input material parameters for these numerical models are basic precondition for successful analysis of the FRC structures. Requested values, mainly of the tensile material properties, can be identified using inverse analysis method from results of available tests on simple structures such as bending beams.

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2. Nonlinear material models for fibre reinforced concrete

Special constitutive material models were developed for description of FRC-material in the nonlinear finite element analysis [1], [2]). They account the high toughness and ductility of FRC, as well as other properties differing FRC material from conventional plain concrete (e.g. form of the descending branch of tensile material law). Several levels of FRC modelling at the material levels are available for performing the nonlinear numerical analysis. The first choice could be utilization of the material models developed for the plain concrete with appropriately adjusted material parameters (tensile strength, fracture energy). The form of the tensile descending branch is in this case an exponential function, which not optimal for the description of FRC response, but its use is rather pragmatic – it is of advantage that the models for plain concrete are very well verified and exhibit rather stable behaviour.

In order to improve the modelling of the FRC tensile behaviour material laws with special forms of the tensile descending branch more suitable for FRC were formulated and implemented. Two models are designed especially for steel fibre reinforced concrete (SFRC). They are derived from plane stress material law for plain concrete. If the fracture energy is known, an objective material law based on the crack band approach can be used. After cracking, the tensile stress drops to certain fraction of the tensile strength. In practical cases the fracture energy value is often difficult to evaluate since in tests it is a hard task to follow the long-persisting descending branch until the zero tensile stress. In such a case a local formulation of the tensile material law is available. It is similar to the previous model but it is formulated directly in terms of strains and does not employ the fracture energy and crack band approach.

The most sophisticated and most general model of FRC material represents an extension to the fracture-plastic constitutive law called CC3-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 the material law assumed for the prescribed characteristic crack band width is adjusted to the actual crack band width.

The FRC material can be in the numerical models also combined with the conventional reinforcement.

3. Inverse analysis of FRC material parameters

An extensive parametrical study on four-point bending beams has been performed by Vítek and Smiřinský [3]. Beams in different configurations made from FRC with various contents of fibres were tested. The test specimens were prepared with different combinations of conventional reinforcement or without, and also beams made from concrete without fibres were made for comparison. Load-deflection diagrams and development of cracks from the performed tests have been documented.

The unreinforced test specimens were simulated by means of nonlinear finite element method in order to determine optimal material parameters of the FRC materials to achieve the best fit to the experimentally obtained response.

The scheme and dimensions of the tested and simulated specimen is shown in Fig. 1. The finite element model of the four point bending beam created in ATENA 2D shows Fig. 2.

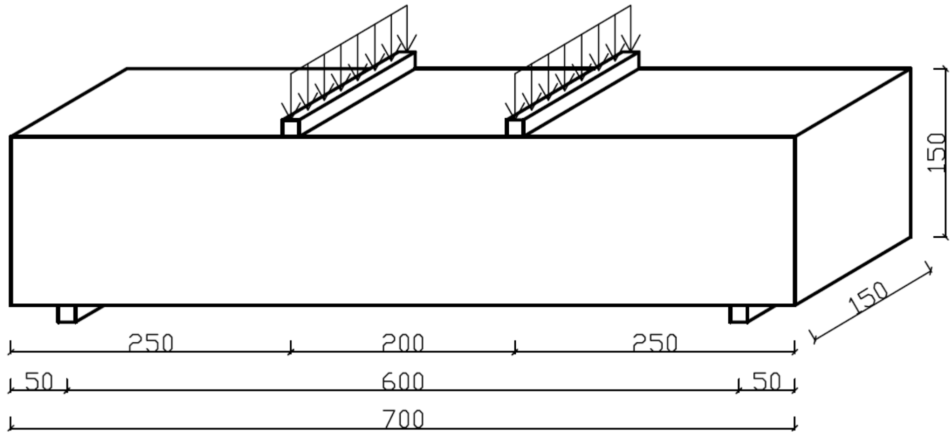

Fig. 1: Scheme of the four-point bending beam tested in [3]

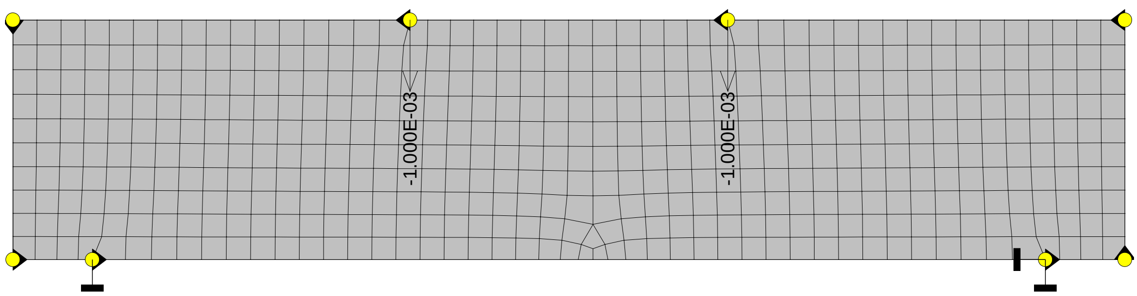

Fig. 2: Finite element model for simulation of four-point bending tests

The basic material parameters were generated in ATENA from the cubic compressive strength of 46 MPa measured in experiments. The original input parameters were adjusted to get best fit with the measured response of the tested beam made from the plain concrete (see Table 1). Comparison of the load-displacement diagrams measured in tests and achieved in the numerical simulation using material model “Nonlinear Cementitious 2” (NLC2) with the adjusted material parameters is shown in Fig. 3. Similar results have been achieved also using other material models (e.g. SBETA)

In the next step, the material properties were randomized using advanced probabilistic system SARA [4], [5]. Regular stochastic distributions with the mean values corresponding to the adjusted values have been used for selected material properties. The results of the stochastic analysis were compared with the measured response for the specimens made with the fibre contents of 40 kg/m^3 (see Fig. 4), and the optimal set of material parameters has been selected (Table 2, left column).

Tab. 1 Material properties of the plain concrete

	plain concrete generated	plain concrete adjusted
Modulus of elasticity [MPa]	35 860	35 860
Poisson's ratio [-]	0.2	0.2
Tensile strength [MPa]	3.1	**2.8**
Compressive strength [MPa]	39.1	39.1
Fracture energy [N/m]	77	**90**
Critical compressive displ. [m]	0.0005	0.0005

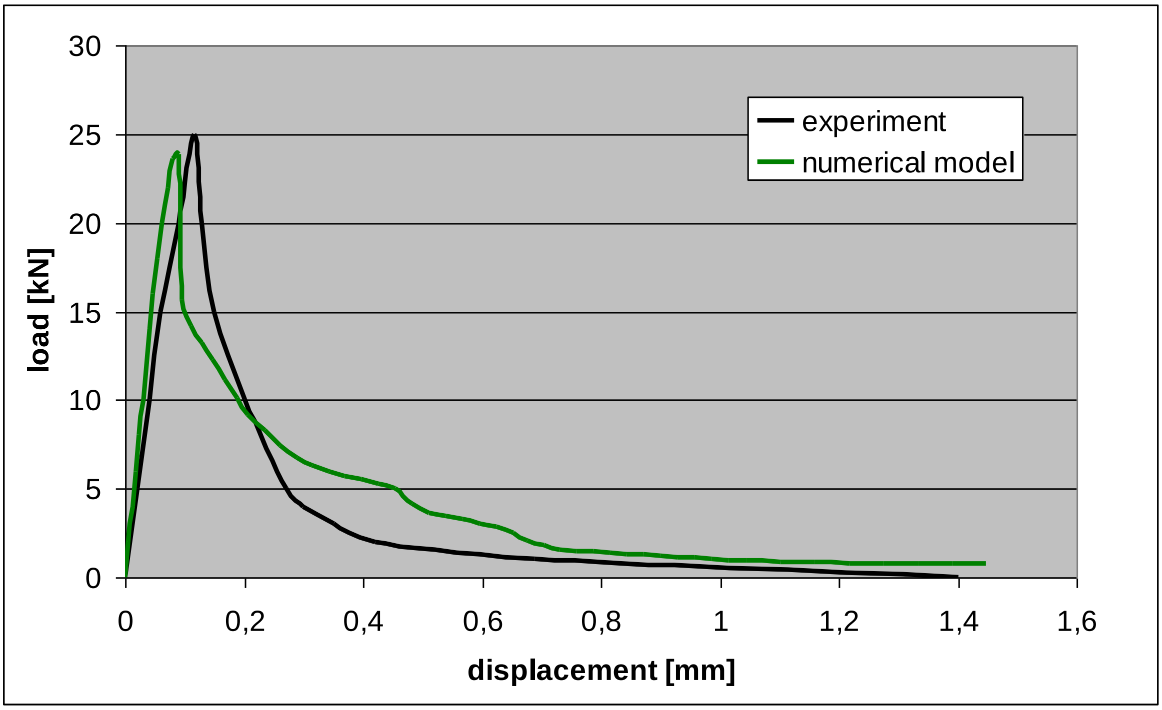

Fig. 3: Comparison of load-displacement diagrams for plain concrete beams

Similar procedure has been performed for the specimens made with the fibre contents of 60 kg/m^3, and also for various nonlinear material models of FRC. The resulting values for material input parameters for FRC with various fibre contents are collected in Table 2.

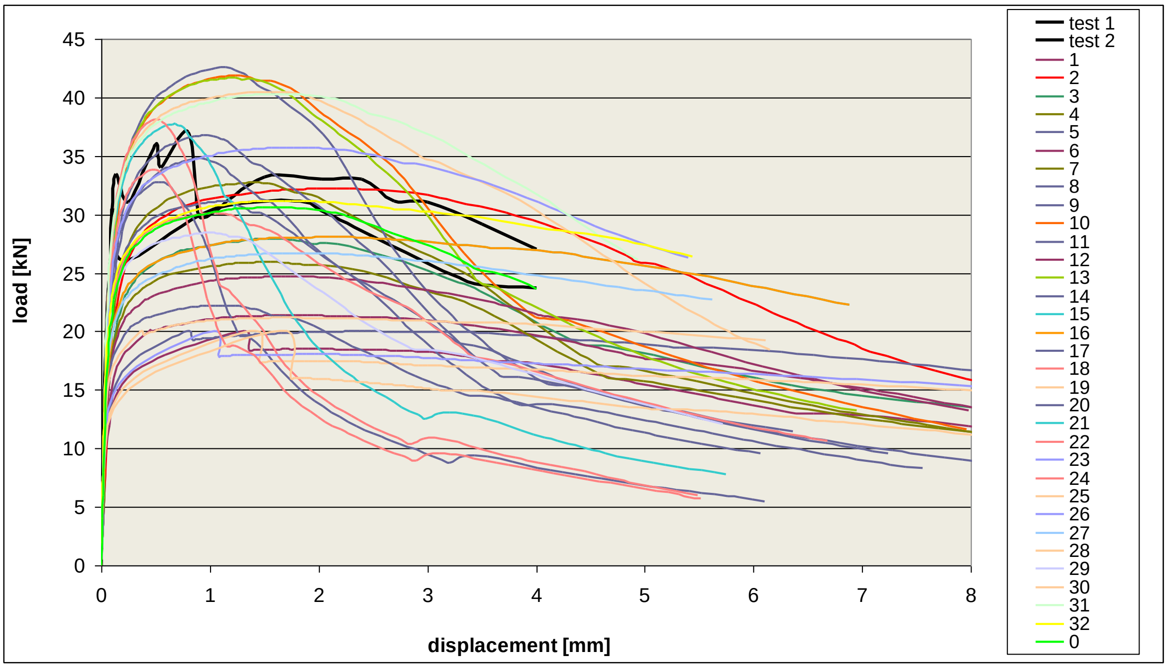

Fig. 4: Load-displacement diagrams from stochastic analysis, comparison with measured response

Load-displacement diagrams for specimens with different fibre contents from numerical simulations using various material models are compared with the measured ones in Figs. 5 and 6. The relationship between the material input parameters and fibre contents has been determined. The multiplicative factor for the fracture energy for plain concrete is between 125-150 for the FRC with the fibre contents of 40 kg/m^3, and ca. 190-225 for the FRC with the fibre contents of 60 kg/m^3.

Tab. 2 Material properties of fibre reinforced concrete

	FRC 40 kg	FRC 60 kg
Modulus of elasticity [MPa]	35 860	35 860
Poisson's ratio [-]	0.2	0.2
Tensile strength [MPa]	**2.0**	**2.5**
Compressive strength [MPa]	39.1	39.1
Fracture energy [N/m]	**11250**	**16880**
Critical compressive displ. [m]	**0.0750**	**0.1125**

The obtained values of fracture energy were also confirmed by Šetková [6], who investigated suitability of different method for determining fracture energy of FRC materials. Based on evaluation of tests performed in Klokner Institute of CTU in Prague (fibre reinforced concrete specimens with fibre contents of 50 kg/m^3) she received fracture energy values in a range between 12000 and 13500 N/m.

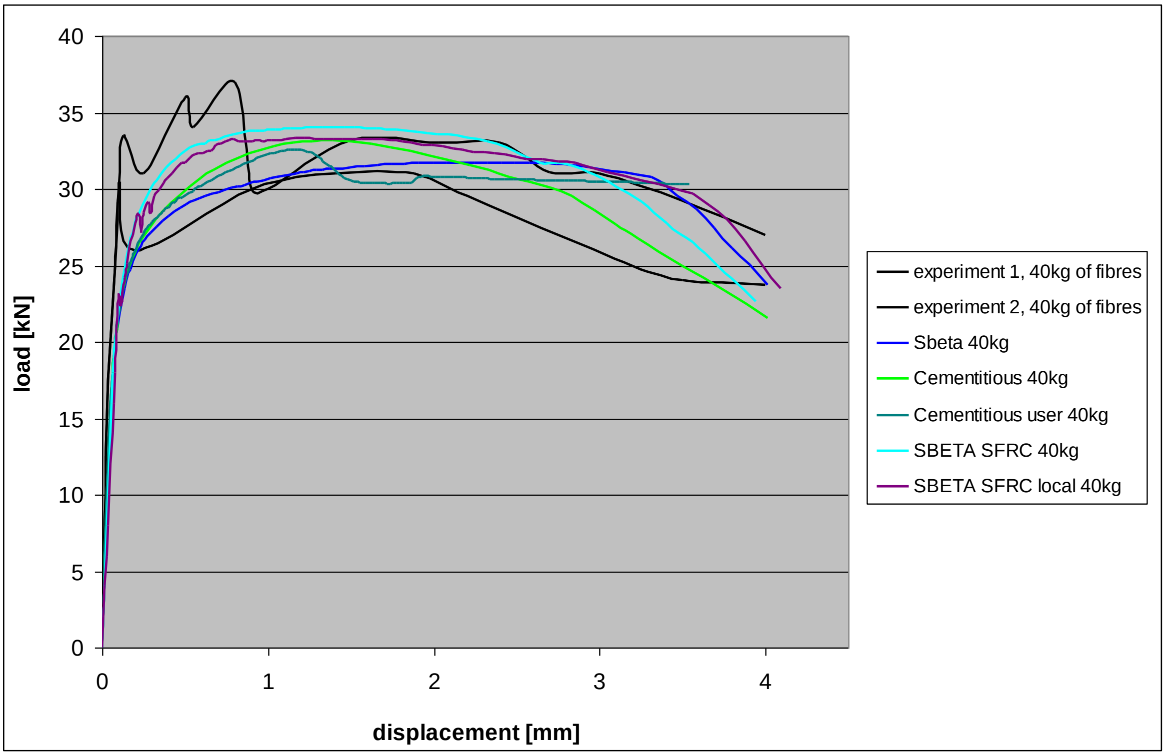

Fig. 5: Comparison of load-displacement diagrams for FRC with fibre contents of 40 kg/m^3

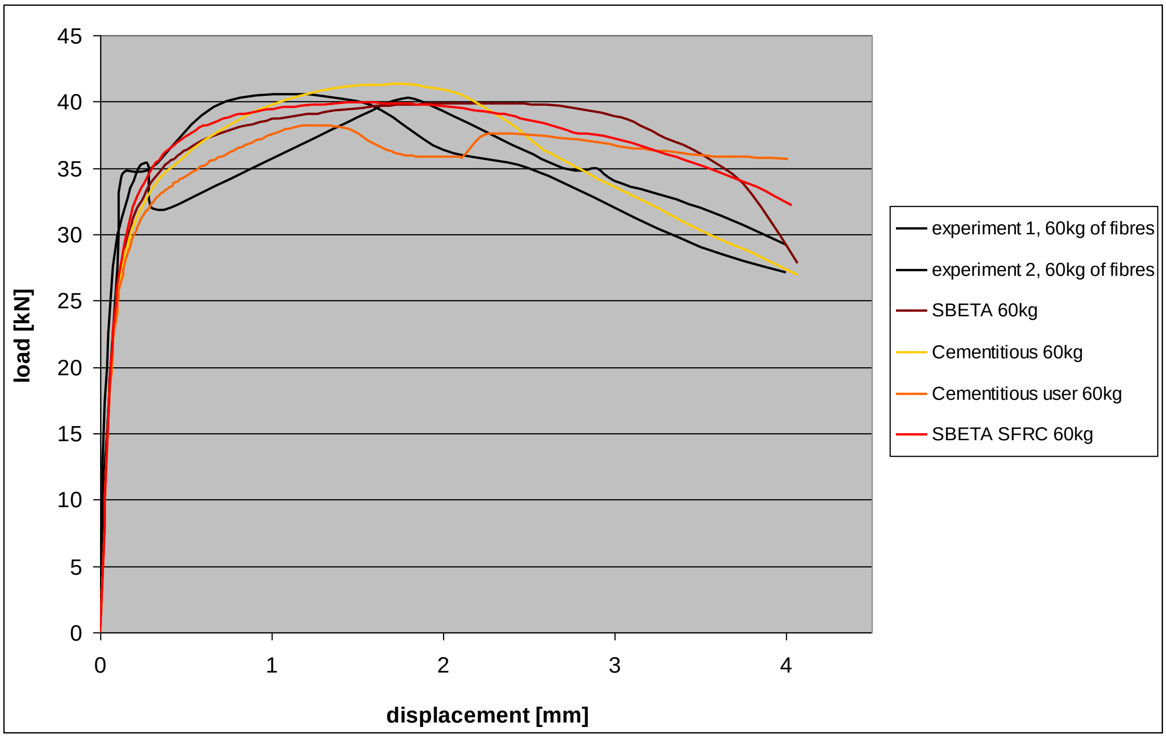

Fig. 6: Comparison of load-displacement diagrams for FRC with fibre contents of 60 kg/m^3

During the material investigations and subsequent numerical analyses significant effect of shrinkage has been recognized. It is necessary to account realistically the shrinkage in the simulation of a structure as a part of the loading process, or at least by adjusting the tensile material properties (reduction of tensile strength).

4. Application example

Using the obtained material values and relationships for FRC materials several practical examples of structures made from FRC have been calculated [2], [7], [8]. Selected results from investigation of behaviour and load carrying capacity of pre-cast tunnel tubings used in tunnel boring method (TBM) are presented here.

The main aim of the study was to determine ultimate load carrying capacity of tubings designed from reinforced concrete, and to compare its response and crack patterns with experiments which have been carried out in Klokner Institute in Prague (Fig. 7). Consequently, an alternative design was examined, where the dimensions of the segment were kept, but instead of the reinforced concrete the fibre reinforced concrete without rebars is used. Such alternate design can save up time, reduce labour and enhance behaviour and performance of the structure and is planed for perspective use within the TBM method.

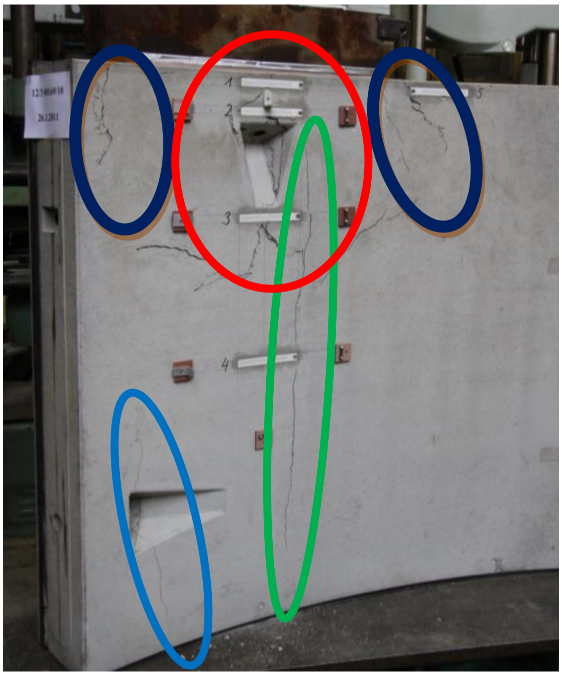

Fig. 7: Crack pattern in RC tubing in experiments

The most important and significant loading case arises during the construction process, when the tubings are loaded in the axial direction by jacks of the TBM, which cause highly localized stress field that might lead to cracking and must be prevented to guarantee serviceability and durability during the lifetime. Therefore, all destructive experiments as well as and numerical analyses were focused on this loading case.

The numerical model of the tubing was created in ATENA 3D engineering according to the original design. The response and crack patterns of the model were very close to the structural behaviour in tests, see Fig. 8. The significant cracking areas in the numerical model are marked and can be compared with damage in the tests of real structure (Fig. 7).

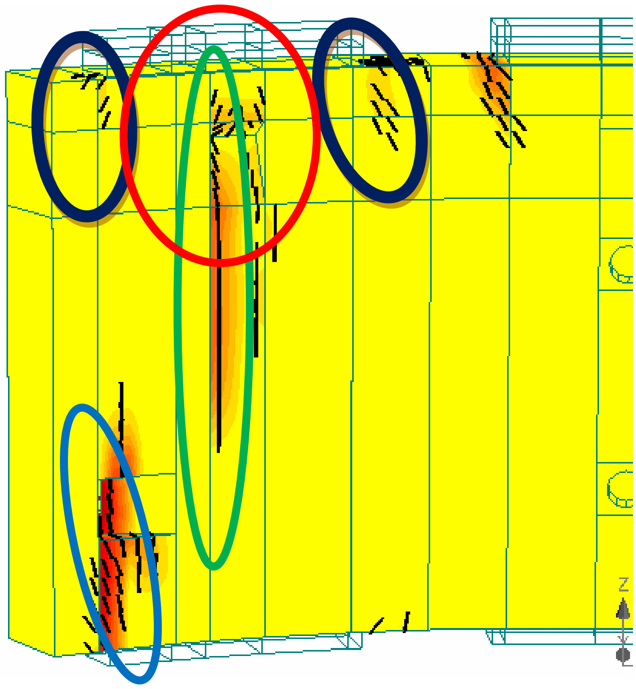

Fig. 8: Crack pattern in RC tubing in numerical simulation

The load-displacement diagram from numerical analysis is shown in Fig. 9 (labelled "RC"), where the ultimate load carrying capacity for this example reached 2.15 multiple of the design load; afterwards the model behaviour was rather brittle and unstable.

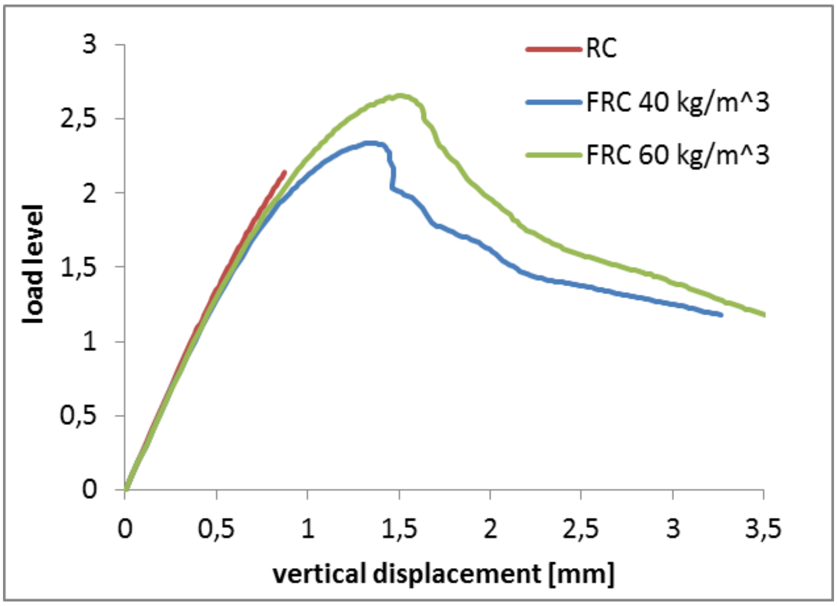

Fig. 9: Load-displacement diagram from numerical simulation of tubing – comparison of reinforced concrete and fibre reinforced concrete

Two numerical alternatives were created by removing the rebars and modifying properties of the material model in order to capture behaviour of FRC with fibre contents of 40 kg/m^3 and 60 kg/m^3. Adjusted parameters of the material model were identified and validated on experiments of three-point and four-point bending tests. The changes in material properties led to more ductile behaviour, higher resistance and lower crack opening (see Fig. 9, data series FRC 40 kg/m^3 and FRC 60 kg/m^3).

Shear resistance of the tubing was numerically investigated on a model with adjusted boundary conditions. This model simulated insufficient precision during construction process. The left support has been removed or weakened – the applied boundary conditions are sketched in Fig. 10, top.

Comparison of numerical results is shown in Fig. 10. The shear resistance of the FRC structure was found to be superior to RC tubing. Crack patterns document larger localized cracks in the RC tubing. In the FRC model the cracks are less localized, they are formed in wider band; consequently the crack opening is lower.

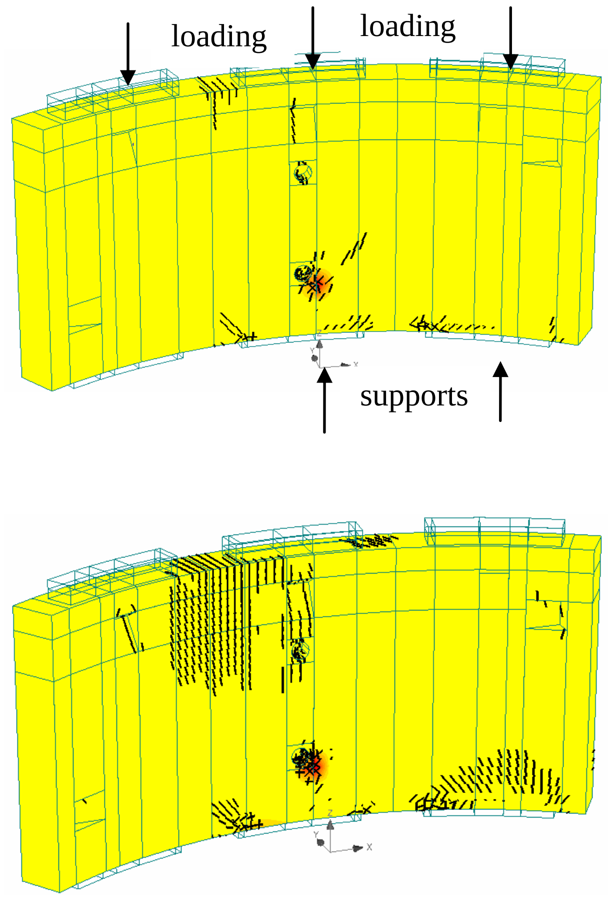

Fig. 10: Comparison of numerically obtained crack patterns at peak load for conventionally reinforced concrete tunnel tubing (top) and fibre reinforced concrete tunnel tubing (bottom)

5. Conclusions

The nonlinear finite element analysis is an efficient tool for investigation and design of fibre reinforced structures. Advanced material models for numerical simulation of fibre reinforced concrete are available, but determining of appropriate material parameters suitable for realistic analysis lies above the usual testing methods. The required values can be efficiently determined using inverse analysis based on stochastic analysis. It has been proved that the nonlinear analysis can be successfully used for analysis of fibre reinforced engineering structures in practice.

Acknowledgements

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6. References

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