NUMERICAL SIMULATION OF SLAB STRIP MADE OF STEEL FIBRE REINFORCED CONCERETE

Kryštof Toman, *

Department of Concrete and Masonry Structures, Faculty of Civil Engineering,
Czech Technical University in Prague, Thakurova 7/2077, 166 29 Prague 6, The Czech Republic.
`krystof.toman@fsv.cvut.cz`

ABSTRACT

This article deals with the numerical prediction of behaviour of a slab strip during bending load test. The slab strip is made of steel fibre reinforced concrete and is reinforced with conventional longitudinal bars in tensile areas. Deformations, tensile strains in reinforcement, compressive strains in steel fibre reinforced concrete and average crack width are predicted in critical cross sections on a basis of numerical simulation in ATENA software before real testing. Experimental verification of the panel's behaviour was carried out by the "fib Working Group WP 2.4.1 Modelling of Fibre Reinforced Concrete Structures" within 2nd Blind Simulation Competition. The result is a comparison between the numerical prediction and the real experiment.

KEYWORDS

Steel fibre reinforced concrete • Non-linear analysis • Software ATENA • SBeta material model • Bending test

1. INTRODUCTION

The purpose of this 2nd Blind Simulation Competition is to verify a capacity of existing FEM-based models to predict behaviour of structural elements made from steel fibre reinforced concrete (SFRC). ATENA software (Advanced Tool for Engineering Nonlinear Analysis) developed by Červenka Consulting s.r.o is used for the author's prediction. This software works with finite element method and primarily it is used for nonlinear analysis of concrete structures. The numerical analysis of the slab strip is realized in 2D space and the SBeta material model was used to describe fibre reinforced concrete.

2. IMPUT PARAMETERS OF SPECIMEN

The input parameters of specimen were taken from the assignment of the competition. The slab strip with a cross-section of 400 mm x 125 mm is supported by three supports. A span of each of the two fields is 3.0 m. The slab strip will be loaded with a pair of equal forces on the upper surface - each of the loads will be placed within half the span. The slab strip is reinforced with conventional longitudinal bars positioned at the bottom region and over the intermediate support.

Material properties of the slab strip were provided by the competition organizer. The panel is made of concrete class C50/60-XD3(P)CL0.20-D_{max}12.5. Material parameters were specified on test specimens. The secant modulus of elasticity in compression is 31.9 GPa, the mean compressive strength determined on cylinders is 57.8 MPa. The concrete is reinforced with HE ++ 90/60 steel fibres with a tensile strength of 1900 MPa. The content of fibres in the mixture is 60 kg/m^3. The residual flexural tensile strength determined according to fib Model Code 2010 recommendations was measured on six specimens. Results of these tests are load – CMOD diagram. The flexural tensile strength ranges from 5.3 MPa to 7.6 MPa. Concrete reinforcement was also subjected to material tests. The yield strength is slightly above 600 MPa.

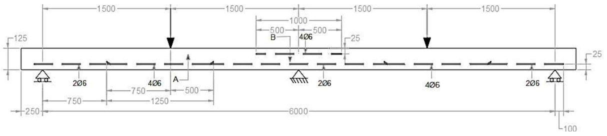

Figure 01: *Geometry of the bending load test*

3. NUMERICAL MODEL

3.1. Geometry

Geometry of the bending load test is based on the assignment. The slab strip is modelled as a one macro element divided by finite element mesh. A size of the finite element was chosen with regard to sufficient adequacy of the results to the required computational time. The finite elements are quadrangular with the sides of the elements 12.5 mm. The panel is divided into 10 elements along the height of the cross section. The lateral supports are modelled as free in the horizontal direction and the middle support is fixed. There are macro elements between supports and surface of slab strip. These macro elements represent distribution bearings and limit the region of singularity.

---

* Supervisor: doc. Ing. Iva Broukalová, Ph.D.

The reinforcing bars are inserted into the model as linear elements parallel to the member axis. A diameter of the bars is considered to be 5.7 mm according to the specifying parameters stated in the competition documents.

3.2. Material model of fibre reinforced concrete

The SBeta material model was used to describe the fibre reinforced concrete. This model is primarily intended for simulations of pure concrete material. Nevertheless, it offers the possibility of adjusting individual parameters and it is possible to capture different behaviour of fibre concrete. The SBeta material model includes the following effects of concrete behaviour: nonlinear behaviour in compression including strengthening and softening, fracture of concrete in tension based on the nonlinear fracture mechanics, reduction of compressive strength and reduction of shear stiffness after cracking. The material model does not affect the real cohesion of the reinforcement and concrete, it assumes it as perfect. It is assumed that the pull out or slippage of the reinforcement in the cross-section will not be the determining factor in the experiment, and therefore this is neglected in the simulation.

The input values of the material model parameters are derived from the assignment. The modulus of elasticity and compressive strength of the concrete correspond exactly to the mean measured values. The tensile strength of concrete is determined from the record of load versus CMOD. The tensile strength is the maximum stress before crack initialization and before the first force drop after loading. It is calculated as the average value from 4 samples with a similar value. Tensile strength is considered to be 5.12 MPa. The fibre concrete option is selected for the tensile softening type and the parameter values (fracture energy, tensile softening parameter c_1 and c_2) are determined by inverse analysis.

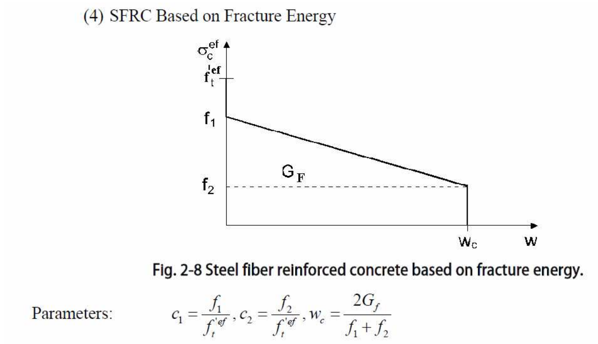

Figure 02: *c_1 and c_2 parameters of steel fibre concrete of material SBeta*

Inverse analysis was performed on tensile test specimens. Such parameters were sought for which the records of the numerical simulation correspond to the actual record from the load test.

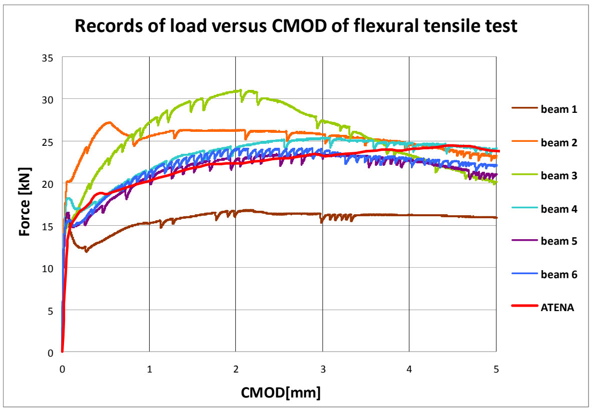

Figure 03: *Comparison of inverse analysis results*

The softening compression was changed to the value w_d = -0.0125m. The other parameters of the material model remained at the default values. All input parameters of the material model are listed in the following table.

Type:	CCSBETAMaterial
Initial elastic modulus:	E = 31.9 Gpa
Poisson's ratio:	v = 0.2
Tensile strength:	R_t = 5,12 MPa
Compressive strength:	R_c = 57,8 MPa
Type of tension softening:	fibre reinforced concrete
Fracture energy:	G_f = 3.998E-03 MN/m
parameter of softening 1	c1 = 0,35
parameter of softening 2	c2 = 0,95
Crack model:	fixed
Compressive deformation on compressive strength:	e_c = -0,002834
Compressive strength reduction of cracked concrete:	c = 1.0
Type of pressure softening:	Crush Band
Softening compression:	w_d = -0,0125m

Table 01: *Parameters of fibre concrete*

3.3. Material model of reinforcing bars

The stress/strain diagram of the reinforcing bars is entered as multi-linear with the same course for the tensile and compressive area. The diagram is composed of 4 points, which are determined from the real stress/strain diagram. These are the origin point, the point of yield strength, the point of ultimate strength and the end point. The specific values are listed in the following table.

Point	Strain [%]	Stress [MPa]
1	0,000	0
2	0,279	600
3	10,000	770
4	11,000	100

Table 02: *points of stress/strain diagram of the reinforcing bars*

3.4. Other setups

Monitoring points were introduced into the model to obtain comparable results. These are mainly monitors of applied loads, deflection at the loaded sections, tensile strain in the reinforcing bars and compressive strain in the FRC. Near the supports and loads, the monitors have been moved to an area where the results will not be affected by the location of the bearings. The results are obtained from a displacement controlled test. The loaded cross section is shifted by 0.5 mm in each calculation step. 500 calculation steps are set to obtain all values up to a 50 mm deflection at the loaded section.

4. RESULTS

4.1. Prediction of slab strip behaviour

The following behaviour of the slab strip is predicted by numerical simulation: up to the total applied load of 22 kN, the main load-bearing capacity of the slab strip linearly increases without significant cracks. In the area between the force of 22 kN and 46 kN, the yield strength of the reinforcement is gradually reached and cracks develop. In this area, the fibres in the concrete structure are activated. After reaching a force of 46 kN, the total load-bearing capacity of the slab strip is exhausted and beyond this limit, there is a significant increase in deformation without a significant increase in load-bearing capacity. The residual strength is affected by the ultimate stress of the reinforcing bars. The maximum force is reached in the last step of the test and it is 55.8 kN.

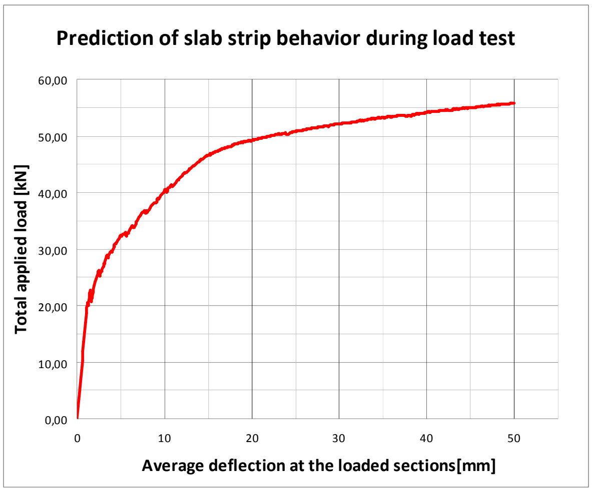

Figure 04: *Prediction of slab strip behaviour during load test*

4.2. Comparison with experiment

On 26 and 28 January 2022, real load tests of two slab strips were conducted in the laboratory of the Structural Division of the Department of Civil Engineering of Minho University (LEST). All the 8 quantities compared were measured during the load tests. Specifically, these are average deflection in the loaded sections, total applied load tensile strain in the flexural reinforcement at the loaded section, compressive strain in the SFRC at the loaded section, tensile strain in the top flexural reinforcement over the intermediate support, compressive strain in the SFRC over the intermediate support, average crack width in the sagging region and average crack width in the hogging region.

The maximum applied load in specimen 1 was 40.52kN and the maximum applied load in specimen 2 was 44.12kN in the experiment. The average value of the maximum applied load is 42.26 kN. The numerical computational model predicted a maximum load capacity of 55.80kN, which is 32% higher. The comparison of other quantities is shown in the following table.

	The real experiment			ATENA	Difference
	Slab 1	Slab 2	Average		
Maximum total applied load [kN]	40,52	44,12	42,32	55,80	**+32%**
Maximum tensile strain in the flexural reinforcement at the loaded section [‰]	3,80	4,57	4,19	23,98	**+473%**
Minimum compressive strain in the SFRC at the loaded section [‰]	-0,75	-1,24	-1,00	-2,45	**+146%**
Maximum tensile strain in the top flexural reinforcement over the intermediate support [‰]	6,76	10,01	8,39	25,1	**+199%**
Minimum compressive strain in the SFRC over the intermediate support [‰]	-4,67	-3,09	-3,88	-2,37	**-39%**
Maximum of average crack width in the sagging region - steel reinforcement level [mm]	0,92	0,72	0,82	0,30	**-63%**
Maximum of average crack width in the hogging region - steel reinforcement level [mm]	-	0,76	0,76	0,29	**-62%**

Table 03: *Comparison of results*

The following graphs summarize the curves of the compared quantities as a function of the average deflection in the loaded section. For the experiment, these are the average values from the measurements of two specimens.

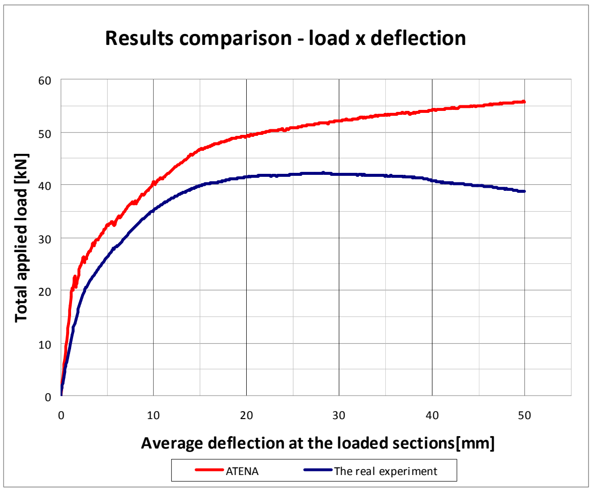

Figure 05: *Results comparison – load x deflection*

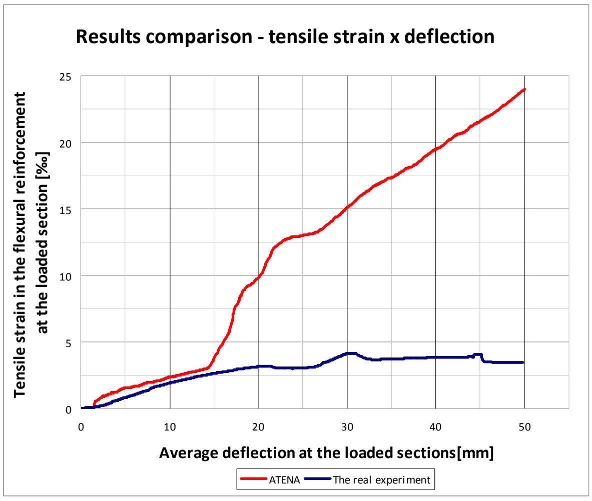

Figure 06: *Results comparison – tensile strain x deflection*

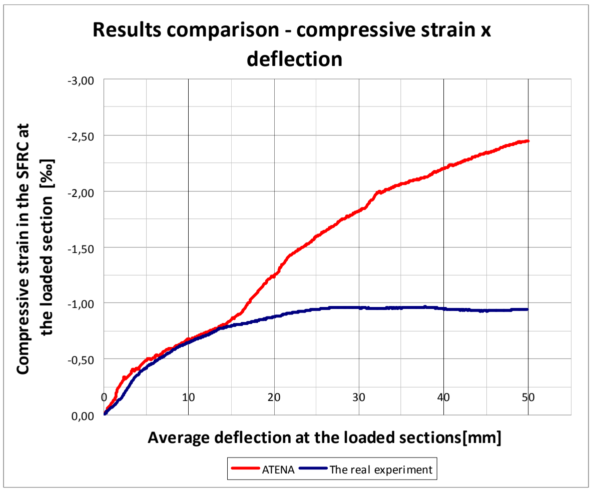

Figure 07: *Results comparison – compressive strain x deflection*

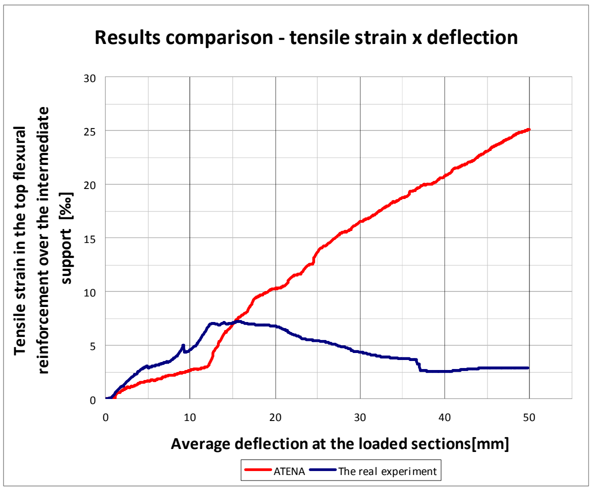

Figure 08: *Results comparison – tensile strain x deflection*

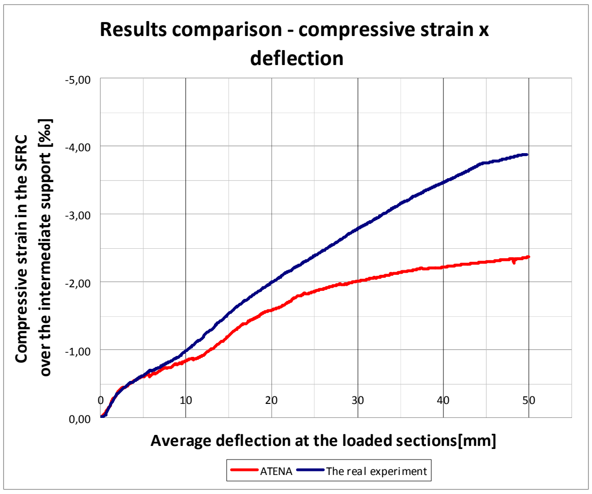

Figure 09: *Results comparison – compressive strain x deflection*

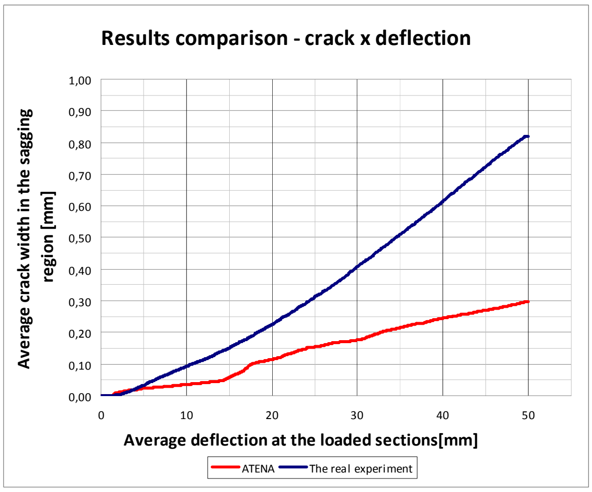

Figure 10: *Results comparison – crack x deflection*

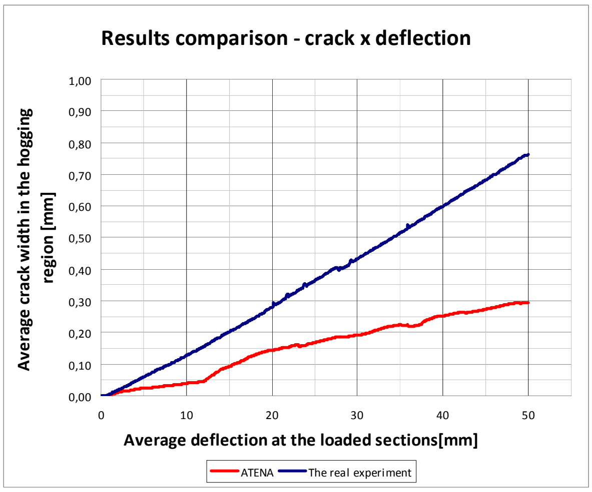

Figure 11: *Results comparison – crack x deflection*

4.3. Evaluation of results

In the area of linear elastic behaviour of the slab strip, the results of numerical simulation and real experiment are very similar. A smaller but still sufficient step can be found in the region of initial crack development, up to approximately 10 mm deflection. Although the real specimen shows a lower modulus of elasticity and a lower load capacity, but considering the many variables that enter into the whole problem, the results in this area can be considered satisfactory. In the deflection region from 10mm, there is a significant effect on the behaviour of the slab strip due to the development of cracks. In the numerical model, there is a considerable stretching of the reinforcing bars and a corresponding increase in the strain of the compressed part of the concrete. In the experiment, the stress along the section height is probably more linearly distributed and does not reach such high values in the extreme fibres. Nevertheless, the cracks are wider in the actual experiment.

Based on the numerical simulation performed and compared with the actual experiment, it can be concluded that the material model SBeta used to describe steel fibre reinforced concrete is suitable in areas of linear elastic material behaviour. In areas after significant crack development, the agreement of the results was poor. In order to obtain sufficient agreement, another set of input material parameters can be sought to match the tests performed on both tensile test specimens and slab strips. Whether such a combination of input parameters exists is the subject of further research.

5. CONCLUSIONS

The behaviour of the plate strip is predicted by numerical simulation. The fibre reinforced concrete is described by the SBeta material model in the ATENA software. The material parameters determined by the tests were applied to the model according to reality. Other parameters were added based on inverse analysis.

By comparison with the real experiment, agreement was found in the linear elastic behaviour of the fibre concrete. In the region beyond the crack development, the behaviour of the SBeta model is more similar to that of concrete and the set of input parameters found does not sufficiently represent the behaviour of fibre concrete. The subject of further research will be whether the parameters can be adjusted to achieve sufficient agreement. An alternative route is to use more complex material models to describe the SFRC.

ACKNOWLEDGEMENTS

This work was supported with the professional help of Associate Professor Ing. Iva Broukalová, Ph.D., and the author would like to thank to her.

REFERENCES

Barros, J., Sanz, B. (2021), *Assignment of 2nd Blind Simulation Competition.*

Červenka, V., Jendele, L. a Červenka, J. (2010), ATENA *Program documentation: Theory.*

EN 14651:200 + A1 2007 (09/2007), *Test method for metallic fibered concrete - Measuring the flexural tensile strength (limit of proportionality (LOP), residual).*

Barros, J., Sanz, B. (2022), *Experimental results of 2nd Blind Simulation Competition.*