NUMERICAL AND EXPERIMENTAL INVESTIGATION OF STRUCTURAL MEMBERS MADE FROM RC AND SFRC

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Abstract

Utilization of steel fibre reinforced concrete (SFRC) for segmental tunnel lining promises potential advantages in comparison to the traditionally reinforced concrete (RC) structures - faster and easier manufacturing, lower risk of corrosion, less damage during transport and installation, etc. However, the practical experience with the SFRC structural members is rather limited (at least in the Czech Republic). Therefore, an experimental program was carried out in order to investigate performance of the SFRC segments - the research program included laboratory tests of full scale tunnel segments made from RC and SFRC under various loading conditions, and also accompanying material tests on SFRC beams. The testing was supported by an extensive nonlinear numerical study modelling the RC and SFRC segments under various loads. Selected results from the experimental and numerical investigations for both RC and SFRC segments are presented and compared. Response of the structural members under service loads and their damage under limit loads are evaluated in order to check and confirm suitability of the SFRC segments for practical utilization.

Keywords: TBM, Mechanized tunnelling, Segmental tunnel lining, Fibre reinforced concrete, FE analysis, Nonlinear material models, Laboratory tests

1 Introduction

Steel fibre reinforced concrete (SFRC) is a promising material for application in precast concrete tunnel lining segments installed by TBM (tunnel boring machine) during tunnel excavation. Full size laboratory tests of both RC and SFRC segments have been performed in order to check their resistance under various loading conditions, representing selected critical states during installation, and in the final structure. The tests were accompanied by an extensive numerical study using nonlinear computer simulation.

2 Testing program and numerical models

Laboratory tests were performed in the Klokner Institute of CTU for both RC and SFRC segments in several configurations representing selected design conditions (Fig. 1). They are labeled as "vault bending" (A), "lateral pressure" (B) and "lateral bending" (C). Numerical simulations, employing finite element technology with non-linear material models for concrete, were performed in order to obtain structural response, propagation of damage and failure. Some of the simulations have been made in advance in order to adjust boundary conditions for the tests such as expected failure forces or support stiffness. Material parameters used in the numerical simulations are summarized in Table 1. In the RC segments the discrete steel bars were modeled using elasto-plastic material law. The material parameters for SFRC material modeling were identified from four-point beam bending tests on accompanying specimens.

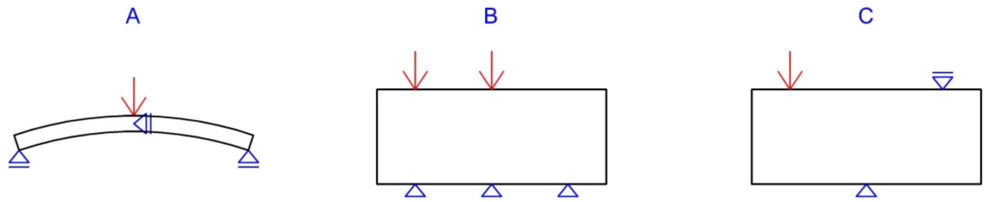


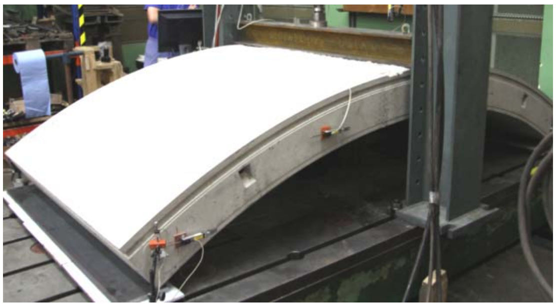
Fig. 1 Scheme of laboratory tests

Table 1
Material parameters for simulation of tests

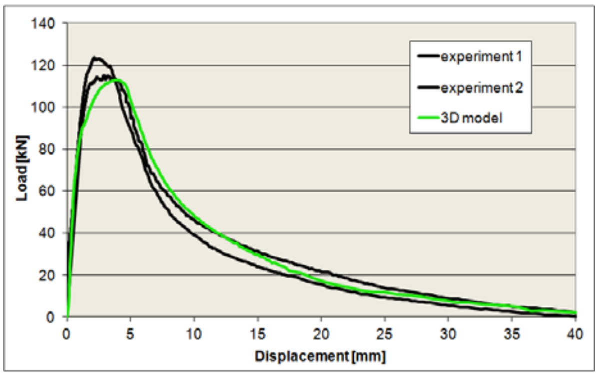
Material model	E [MPa]	μ [-]	f_t [MPa]	f_c [MPa]	G_f [N/m]	w_d [m]	RC [-]
Plain concrete	40600	0.2	4.425	-67.3	111	-0.0005	0.2
FRC (40 kg/m^3)	40600	0.2	**2.265**	-67.3	**2800**	**-0.0125**	**1**

3 Vault bending tests

Subject of this experiment was to clarify behaviour of the segment under local lateral load, in particular in case of SFRC segment. The test setup in the laboratory of Klokner institute can be seen in Fig. 2a. Load-deflection diagrams from two tests of SFRC segments are the black (dark) lines in Fig. 2b. The final resulting crack in the SFRC segment is shown in Fig. 3a.



(a) Laboratory tests setup

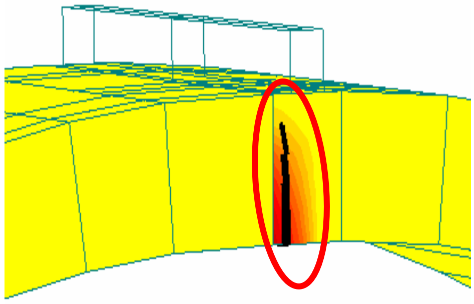


(b) Comparison of load-deflection diagrams for SFRC segments - experiment vs. numerical model

Fig. 2 Vault bending

Numerical model of the segment was created in ATENA 2D and ATENA 3D engineering according to the original design. The load-displacement diagram from numerical analysis of the SFRC segment is shown in Fig. 2b (labelled "3D model") and compared to the experimental ones. The numerically obtained ultimate load carrying capacity of 113 kN is equal to the measured capacity of the experiment No. 1; all the response curves have the same character. Development of bending cracks in the model was very close to the structural behaviour in experiment. Compare the final crack in Fig.3b with the crack from experiment (Fig. 3a); the significant cracking areas are marked. The cracks in both experiment and numerical analysis are here strongly localized even in the SFRC material.

(a) Experiment



(b) Numerical simulation

Fig. 3 Comparison of cracks in SFRC segment – vault bending

4 Lateral pressure

This test simulates action of the TBM machine press devices during installation and assembly of segments. The laboratory tests and numerical simulations were performed for RC segments (comparison of resulting failure crack pattern see Fig. 4) as well as for SFRC segments. The model of SFRC segment show higher number of cracks (crack band) with smaller width (Fig. 5). The calculated capacity of SFRC segments is slightly higher than the capacity of RC segment, and the failure regime is more ductile.

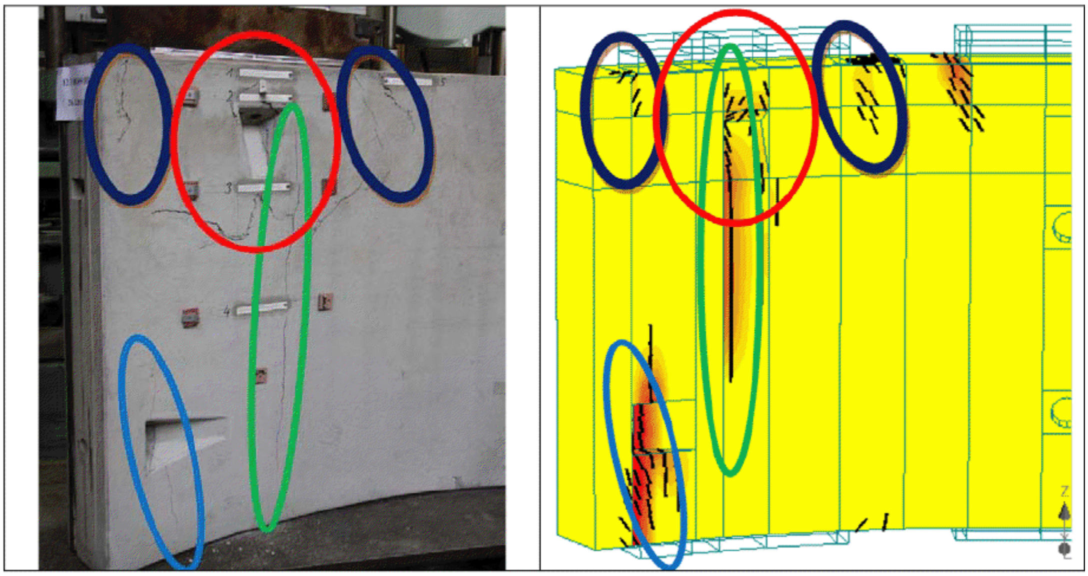


Fig. 4 Laboratory test (left) and FE model (right) of RC segment – location of principal cracks

5 Comparison of RC and SFRC in tunnel segments

The RC segments have a clear advantage, that they can be reinforced relatively strongly in the direction where tensile forces appear. Segments made of SFRC are not capable to resist the increasing tensile stress when it is necessary. On the other hand the fibre reinforcement has technological advantages and may bring savings in production of segments. Another advantage of segments made from SFRC lies also in lower sensitivity to local damages during assembly of the lining. It is necessary to take into account the design conditions in the underground space, which provide the geotechnical loading including the underground water pressure. The other loadings given by construction technology (production, transport and assembly of segments) may define other unfavourable loadings. If all these factors are taken into account, it is a moment for decision if segments made of SFRC may be designed or if the bar reinforcement is necessary.

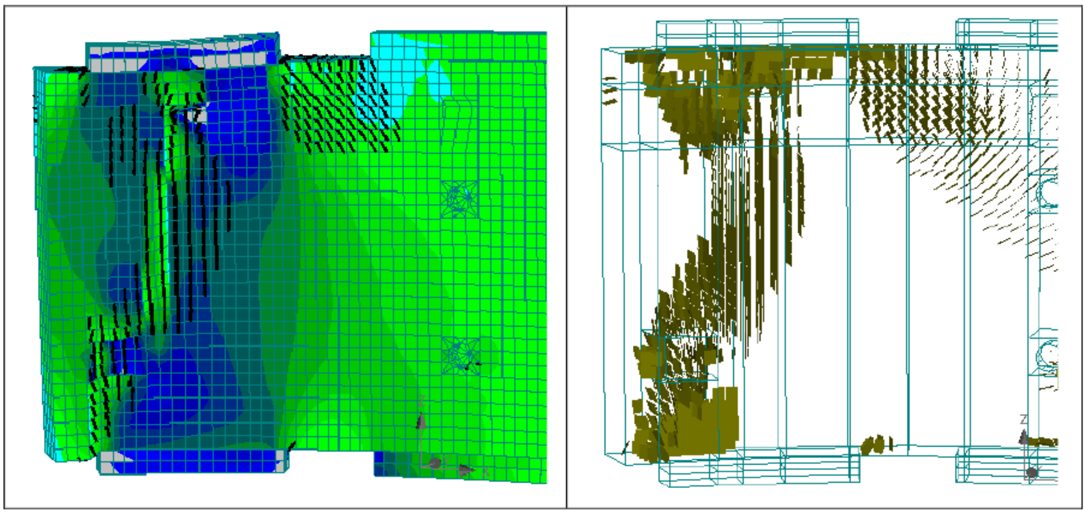


Fig. 5 Cracks in SFRC segment model

6 Conclusions

Testing and numerical modelling of RC and SFRC has been performed in order to check their performance in selected critical design and loading situations. It has been proved that using of SFRC for production of tunnel segments is a prospective option. The numerical models successfully predicted and accompanied the laboratory tests; in the numerical model a more detailed evaluation of structural response is available compared with experiments. Possible future utilization use of the SFRC tunnel segments in the Czech Republic was successfully confirmed by construction of the 15 m long test section in the Prague metro line A extension.

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