LABORATORY TESTING AND NUMERICAL MODELLING OF SFRC TUNNEL SEGMENTS

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steel fibre reinforced concrete, segmental tunnel lining, laboratory testing.

1. INTRODUCTION

Steel fibre reinforced concrete (SFRC) is a promising material for application in precast concrete tunnel segments. The following paper is focused on material properties of SFRC and comparison with concrete segments reinforced by steel cages. The experimental results on SFRC testing beams are presented. Comments on numerical modelling of SFRC beams indicate that there is a field for future research. If the geotechnical conditions are reasonable and generated bending moments in the tunnel lining are not high, the SFRC may represent a cost-effective alternative to the precast concrete segments reinforced by rebars.

2. MATERIAL TESTING

The fibre reinforced concrete with the matrix class C50/60 was prepared with 50 kg/m3 of fibres Dramix RC-80/60-BN. Experiments verifying the bending performance were carried out. The two arrangements of tests were applied. The RILEM test assumes notched beams with the cross-section 150 x 150 mm with the span of 500 mm long loaded by 3 points bending. The test according to the German standards which is used also in the Czech Republic assumes a beam of the same dimensions of the cross-section without notch, but of the span 600 mm long. The loading by two forces acting in the thirds of the span represents a 4 points bending test. The beams produced from fibre reinforced concrete were examined using both 3 points and 4 points bending tests.

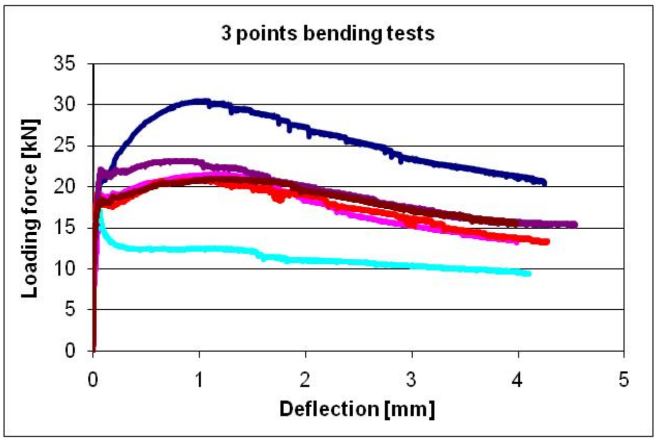

Fig. 1 Experimental results according to the RILEM tests measured on notched beams

The dependence of deflection at the midspan on the loading force was measured at both tests, and the dependence of crack mouth opening displacement (CMOD) on the loading force was measured at the three points bending test. The results of the tests exhibited a certain statistical scatter, which is at fibre reinforced concrete elements quite usual. The load-displacement diagrams are plotted in Fig.1, and 2. The diagram CMOD x Loading at three points bending tests is plotted in Fig.3. The similarity of the diagrams in Fig.1 and 3 is apparent, due to the mechanism of failure of the specimen under the bending.

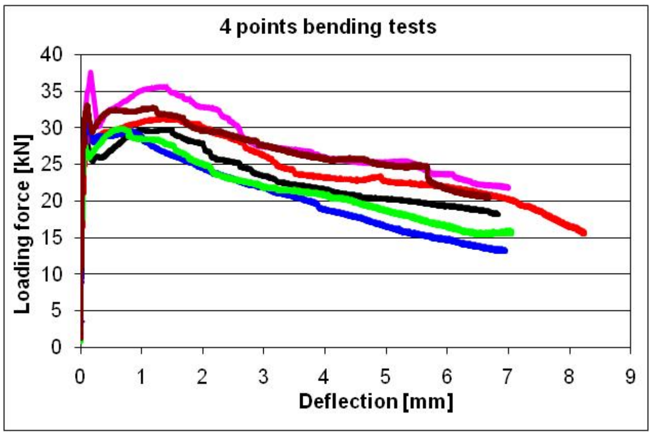

Fig. 2 Experimental results according to the German tests measured on beams without notch

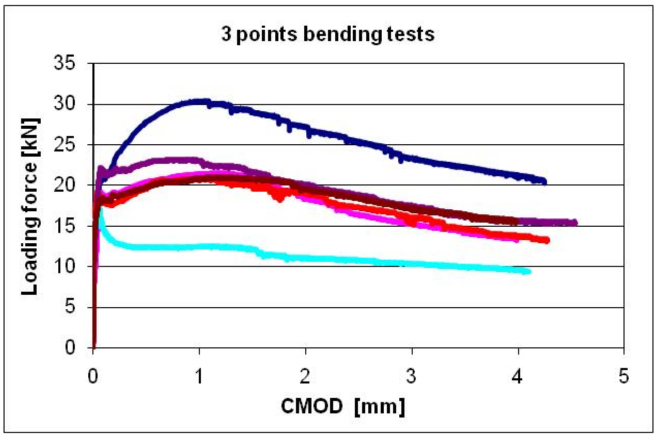

Fig. 3 Crack mouth opening displacement (CMOD) on the notched beams

It is quite clear, that the deflection and CMOD are mutually related. The failure takes place in one section; the remaining parts of the tested beams may be considered without any damage as stiff elements. Under such assumption a geometrical mechanism may be assumed which defines the direct dependence between the deflection of the beam and the CMOD.

The objective of the tests was: i) Comparison of the behaviour of the material with other similar materials (e.g. with SFRC reinforced by other fibres) and ii) to get experimental results, which provide a basis for determination of the parameters describing the performance of SFRC applicable in numerical models.

It may be seen from the load-deflection diagrams that the results exhibit large statistical scatter. It is unfortunately usual at SFRC. The larger scatter was observed at specimens with the notch. It may be explained by the fact, that the section which fails is given in advance, i.e. the response is dependent on one section. On the other hand the specimens without notch fail in the weakest section; there is an entire central area of the beam which potentially fails, and the scatter becomes reduced. The four points bending tests have longer descending branch of the diagram, which provide more precise data for numerical modelling (Fig.4).

4. COMPRESSION OF KEY SEGMENTS

Testing of both RC key segment and SFRC key segment was realised in Klokner laboratory of the Czech Technical University in Prague. The segments were produced (Fig.4) in cooperation with Prague metro line A extension, where mechanical excavation using TBM machines is currently ongoing. Key segments were loaded by axial force to simulate pressure from rams located on the back part of the tunnelling shield during its penetration into the ground (i.e. tunnel lining is loaded in longitudinal direction).

Fig. 4 Casting (left) and demoulding (right) of SFRC key segment

Values of acting force and corresponding values of deformations were continually recorded. Deformations were monitored by both potenciometers and tensometers located on the segment surface (see Fig. 6).

Key segments were placed on the testing machine. 9 mm thick plastic plate was placed on the upper part of the segments and steel plate 20 mm thick was placed over it. Both plates corresponded with dimensions and material of tunnelling shield rams.

The acting force was increased with 300 kN steps, the segment was unloaded to 90 kN between all loading steps.

Internal surface (L) External surface (P)

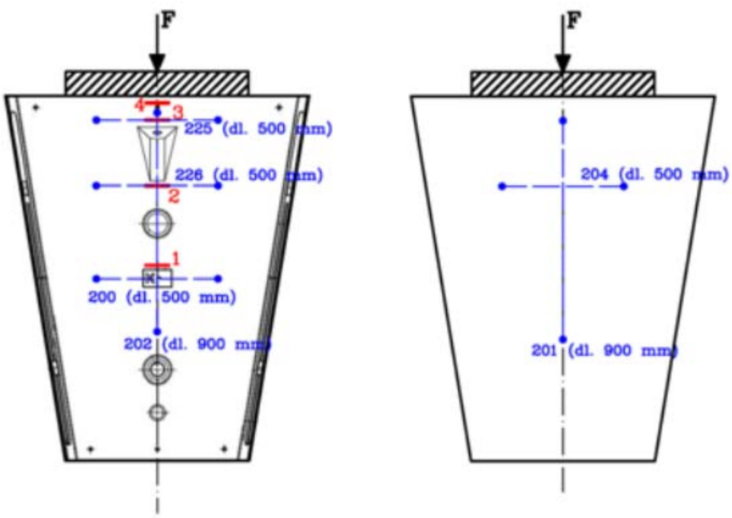

Fig. 5 The test arrangement including locations of potenciometers and tensometers

Tab. 2: Comparison of resulting measured forces of compression test realised on two key segments with a different reinforcement

Concrete	RC	**SFRC**
The first crack - force F_{cr} [kN]	3300	**4200**
Maximum reached force F_u [kN]	5868	**cca 7200**

A) SFRC key segment

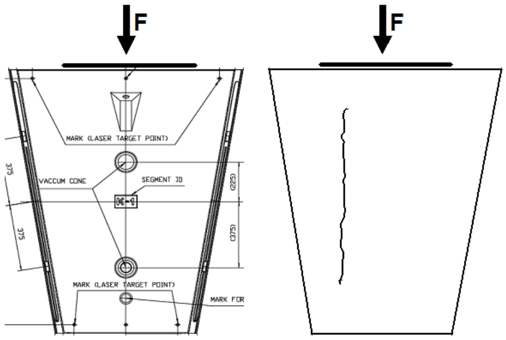

Fig. 6 Record of macrocrack location – SFRC key segment – $F_{fc,cr}$ = 4200kN

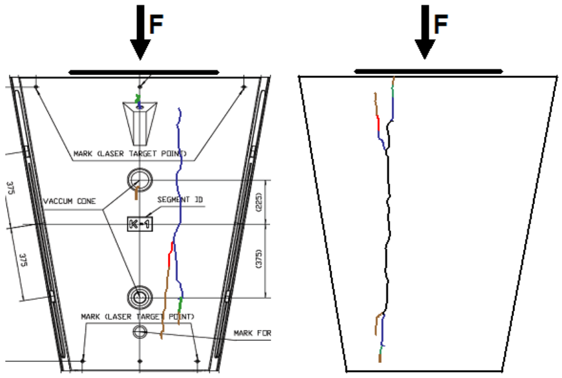

Fig. 7 Record of macrocrack location under maximum load – SFRC key segment – $F_{fc,u}$ = 7200kN

B) RC key segment

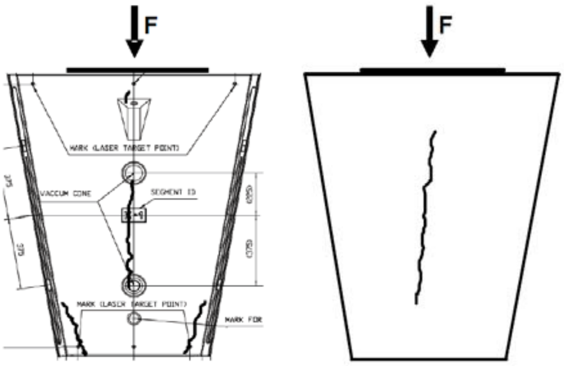

Fig. 8 Record of macrocrack location – RC key segment – $F_{c,cr}$ = 3300 kN

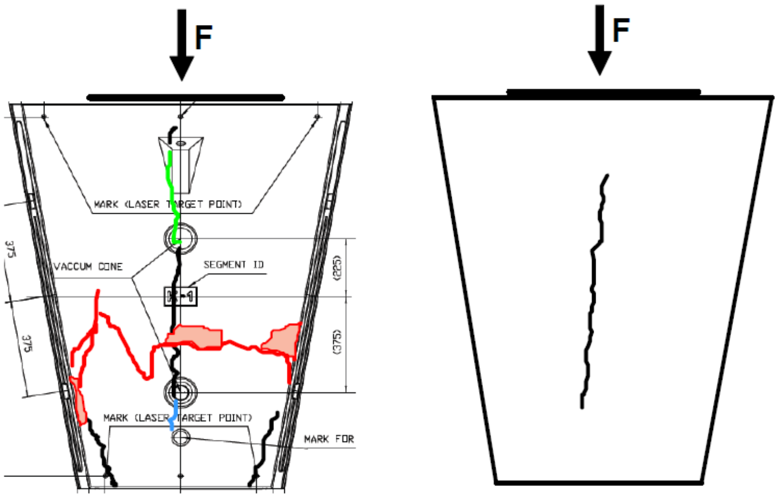

Fig. 9 Record of macrocrack location under maximum load
– RC key segment – $F_{c,u}$ = 5868kN

Fig. 10 Comparison of damaged key segments after reaching their capacity: (RC key segment – left, SFRC segment - right)

The tested SFRC key segment showed in both load cases (macrocrack generation and compression capacity) higher values, which were about 25% than in case of RC segment.The load value of the first macrocrack generation is namely important, because it correspond with SLS (serviceability limit state). Testing results showed about 3 times higher capacity in comparison to required maximum axial force of tunnelling shield on Prague metro line A extension F_E = 2430 kN.

4. COMPRESSION OF RECTANGULAR SEGMENTS

Rectangular segments were also tested. A setting of the test is in Fig.11. Software ATENA was used for numerical modelling of the test. The software allows simulating non-linear behaviour of concrete, namely propagation of failures. The models corresponding with realised testing were calculated using finite element method in ATENA 3D Engineering.

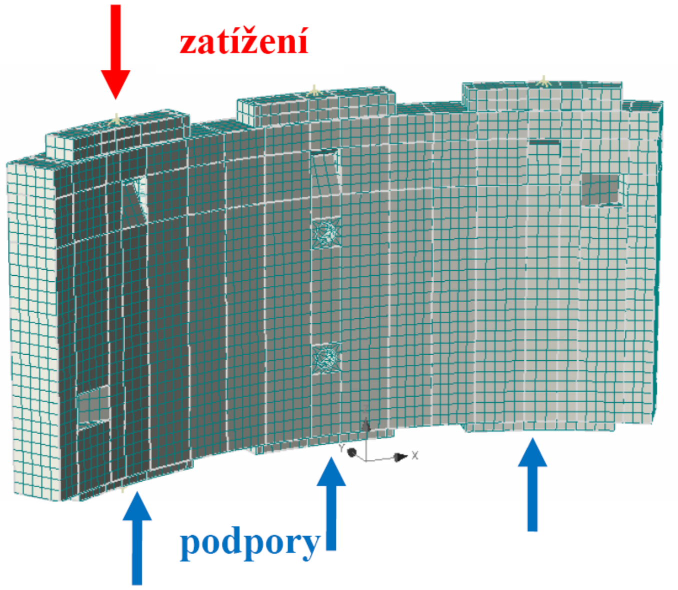

Fig. 11 Loading of rectangular segment

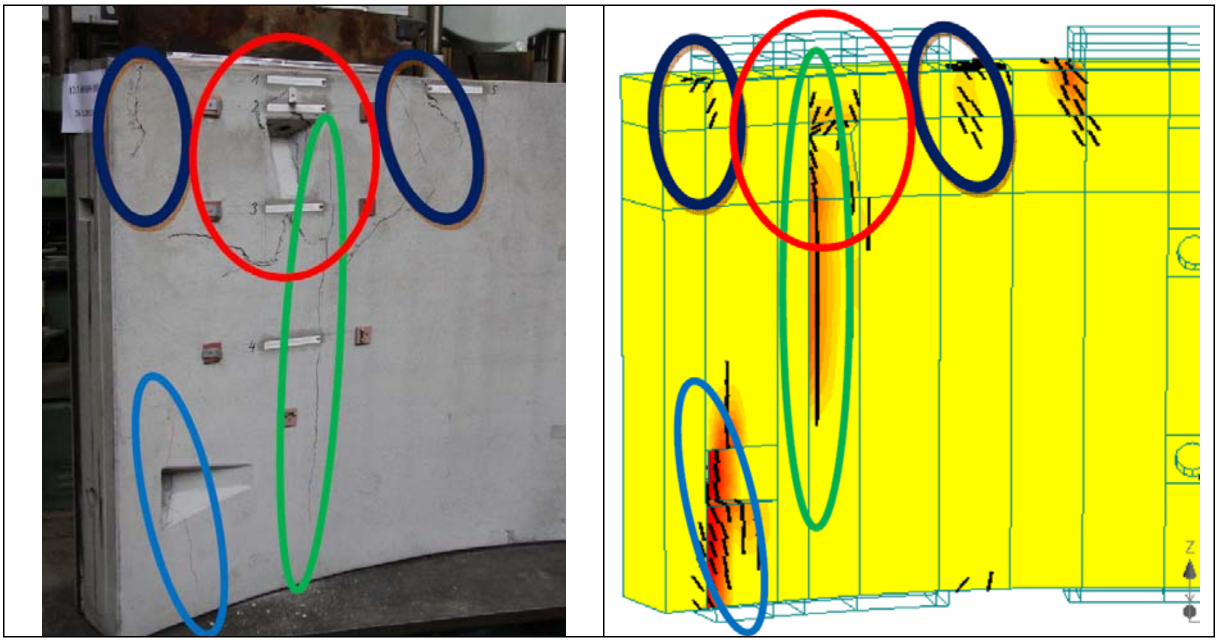

Fig. 12 Result of testing and result of modelling of RC segment in ATENA – comparison location of cracks

Comparison of testing results and modelling results is in Fig. 12. Location of cracks on segments after loading in laboratory is on left hand side, location of cracks resulting from numerical modelling in ATENA is on right hand side. The vertical cracks are prevailing in both cases, they go through the whole segment (green colour). Moreover cracks in area of acting load can be seen (dark blue colour) and cracks in area of supports (light blue colour).

A comparison of calculated stress – strain diagrams of RC segment and SFRC segment with two dosages of fibres (40 a 60 kg/m^3) is in Fig. 13. Calculated capacity of SFRC segments is higher, failure is ductile. The model of SFRC segment show higher number of cracks with smaller width.

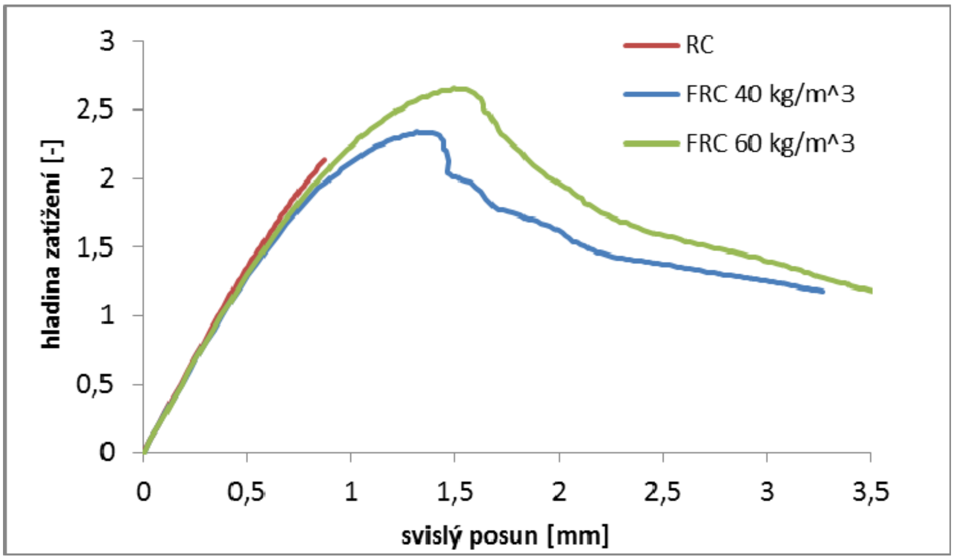

Fig.13 Stress-strain diagram of RC and SFRC segments with various fibre dosages. Load 1.0 corresponds with design ram load 2.43 MN

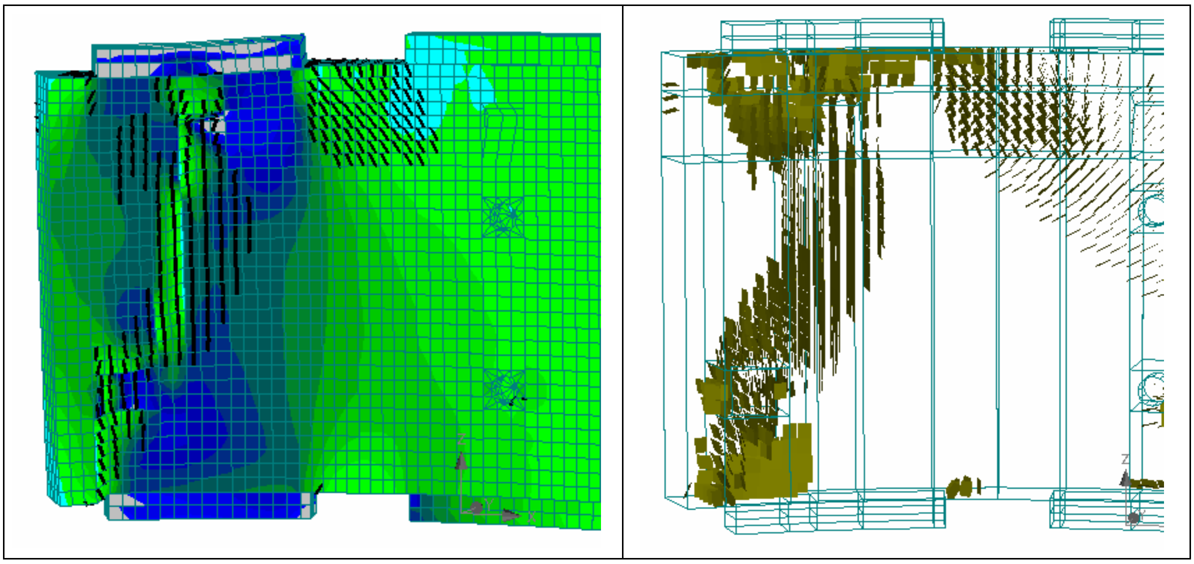

Fig. 14 Location of cracks in SFRC segment model

7. COMPARISON OF RC AND SFRC IN TUNNELS 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. The fibre contents would be too large, which would lead to technological problems. On the other hand the fibre reinforcement has technological advantages and may bring savings in production of segments. The advantage of segments made of SFRC lies also in lower sensitivity to local damages during assembly of the lining. Therefore 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 the 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. Of course the combination of bar and fibre reinforcement is also possible, but then the main advantage of simplification of the production would be lost.

8. CONCLUSION

The paper describes the different issues which are to be taken into account if tunnel segments should be designed from SFRC, the results of axial loading of RC and SFRC key segments are compared. The major points are summarised in the following items:

1. The advantage of using SFRC for tunnel segments is mainly in easier production and in lower sensitivity to damage during manipulation and assembly of segments at some loading stages.
2. The segments made from SFRC are convenient if the geotechnical conditions (permanent loading by ground) do not require the bar reinforcement, i.e. if the shape of the lining, generated load and thickness of the lining provide conditions for low ratio of steel reinforcement (mainly in ultimate limit state).
3. The temporary loading must be taken into account as a secondary effect, if the conditions under the item 2 are satisfied. Mainly the thickness of the segmental lining is important for reduction of the stresses during assembly of the segments.
4. A great attention should be paid to the production technology of segments made of SFRC. The distribution of fibres should be uniform as much as possible, which requires a very precise selection of constituents of concrete and fibres, and well developed technology of mixing. Two ways are possible, relatively stiff mix and very efficient compacting using vibration, or self-compacting (or almost self-compacting) concrete with no or very limited compacting. The second alternative is more convenient due to the higher reliability and better environmental conditions in the precasting plant. It is necessary to take into account a significant statistical scatter of the SFRC response which is much larger than that of RC.
5. Numerical modelling of SFRC is an essential condition for correct design of structural elements. The models for simple technical design are well developed, models for numerical analysis require further research, in order to fit well the progressive material damage until failure.
6. The performance of segments made of SFRC and RC cannot be directly compared, since it is only a part of the system. The complete design and technology of the tunnel lining including all the costs during the complete service life may be compared and from such data a conclusion, which segments are more convenient, may be obtained.

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