STEEL FIBER REINFORCED CONCRETE PRECAST TUNNEL SEGMENTS: DESIGN USING NONLINEAR ANALYSIS

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ABSTRACT: Utilization of the steel fibre reinforced concrete (SFRC) for segmental tunnel lining promises potential advantages in comparison to the traditionally reinforced concrete (RC) structures - efficient manufacturing, lower risk of corrosion, less damage during transport, etc. This paper describes design of precast tunnel segments from the steel fibre reinforced concrete 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 modelling 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 bending and compressive tests using inverse analysis procedure. Design of the segmental tunnel lining has been performed based on a combination of the non-linear finite element analysis and laboratory tests of the precast SFRC segments. The numerical investigation and design of the structure - precast tunnel segments for TBM technology - was performed for various construction stages and various loading situations (manipulation shortly after concreting, storage and transport of segments, pressure of TBM machine, water and ground pressure, traffic load). During project preparation and design procedure the results from numerical simulation of SFRC tunnel lining segments were compared with the experimental evidence. Response of the structural members under service loads and their damage under limit loads were evaluated in order to verify and support NLFEA-based design of the SFRC tunnel segments.

1. INTRODUCTION

As part of modernization of the railway line Rokycany – Pilsen two single track railway tunnels are constructed. Vertical alignment is characterized by a uniform slope of 8 ‰ in the entire length of the tunnel, railway track declines in the direction of stationing, i.e. from Rokycany to Pilsen. Directionally, axis is led in straight in the Homolka massif and in a curve with radius R=1.785 km in the Chlum massif. Tunnel boring machine (TBM) with shield EPB/Hardrock is used for tunnel construction. The planned train speed is 160 km/h, prospectively up to 200 km/h. Figure 1 shows the overall situation of the tunnels. Lengths of southern and northern tunnel are written in Table 1.
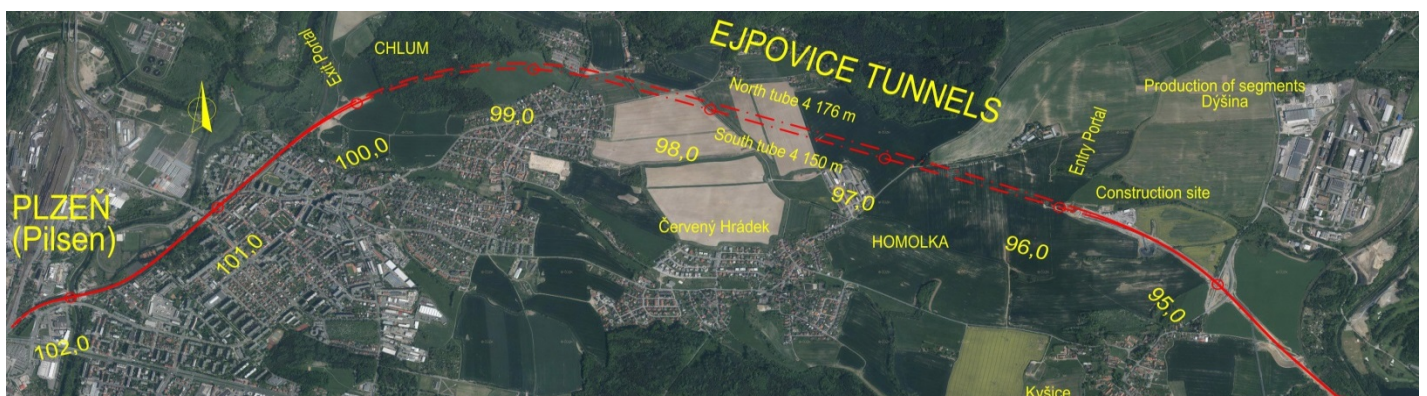

Figure 1: The overall tunnel situation.

1.1 GEOLOGY

Geological structure of the area is quite complicated. The oldest unit includes Proterozoic rocks mostly represented by dark shales and partially by light siltstones, geology in Chlum is created mostly by spilite. From the hydrological point of view, we can distinguish two basic units - interstitial permeable Quaternary environment and permeable environment along fractures underlying Proterozoic siltstone and greywacke or spilites. The described environment creates common shallow aquifer of groundwater linked to weathered zone and near-to-surface disconnection of fissures. The groundwater level is free, conformal with the shape of the Earth's surface and directly dependent on the quantity and intensity of rainfall. The tunnel is situated beneath the water table. The geology of the massifs is in Table 2. Figure 2 shows longitudinal section of the southern tunnel.

Table 1: Length of tunnels

Tunnel	Length
JTT	4150 m (4110 m bored)
STT	4176 m (4134 m bored)

Table 2: Geology of the massifs

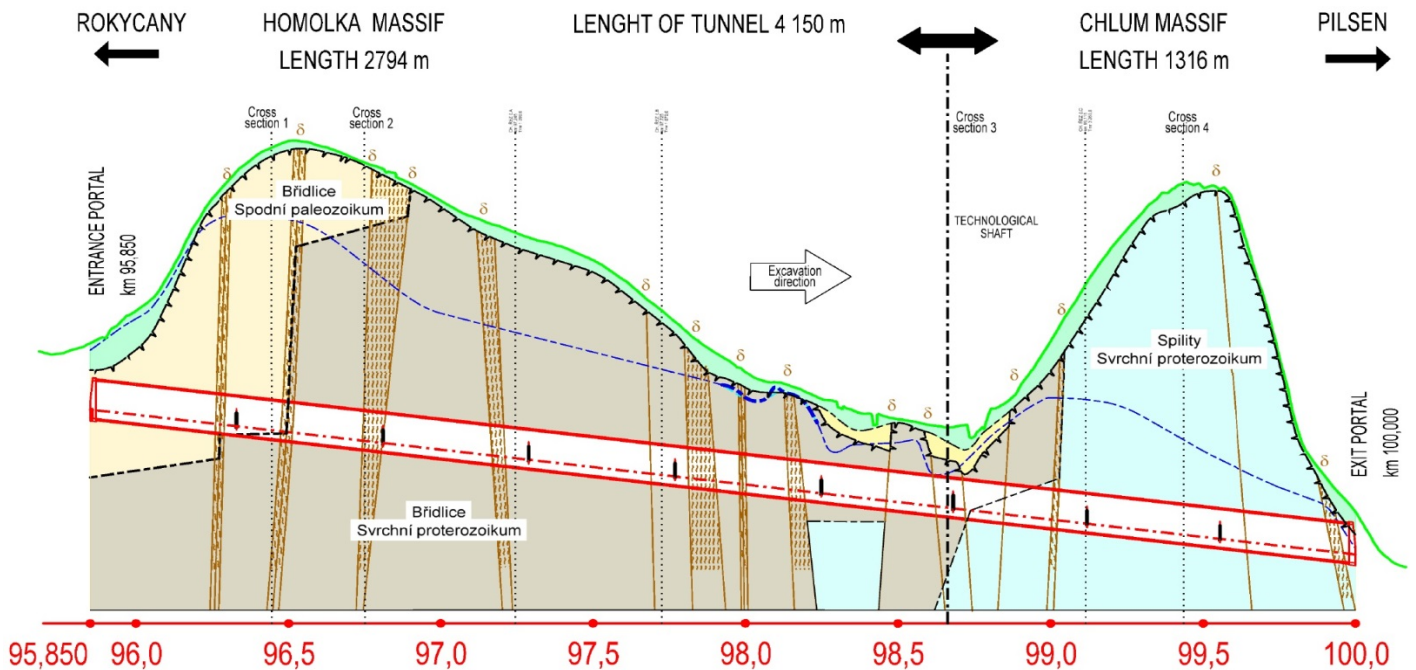| Massifs	Geology	Label
Homolka	Proterozoic and Palaeozoic shales, tectonically disturbed, heavily weathered to weathered	R3/R4 - R6
Chlum	Spilite - Upper Proterozoic	R2/R3

Figure 2: Longitudinal section of the southern tunnel.

2. TUNNEL STRUCTURE

2.1 SEGMENTAL LINING

The circular segmental lining is used for the tunnels. It is designed as a single shell with closed insulation system. The lining consists of precast SFRC segments and reinforced concrete segments with inner radius 4.35 m in both cases. The segment thickness is 0.40 m and the width of load carrying ring is 2.0 m. Concrete used for the lining corresponds to the class C45/55. Composition of lining (one ring) is shown in Figure 3 and 4 and it consists of 7+1 segments, the segments labelled as A and E are keystones (Figure 5 and 6).
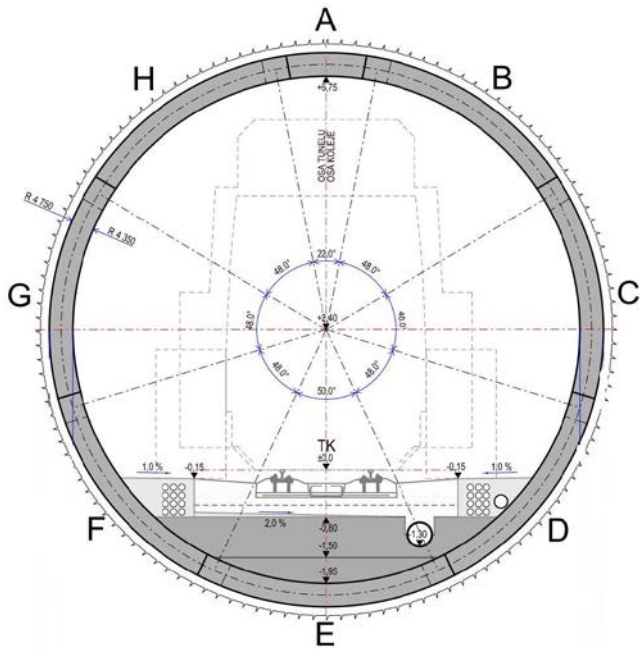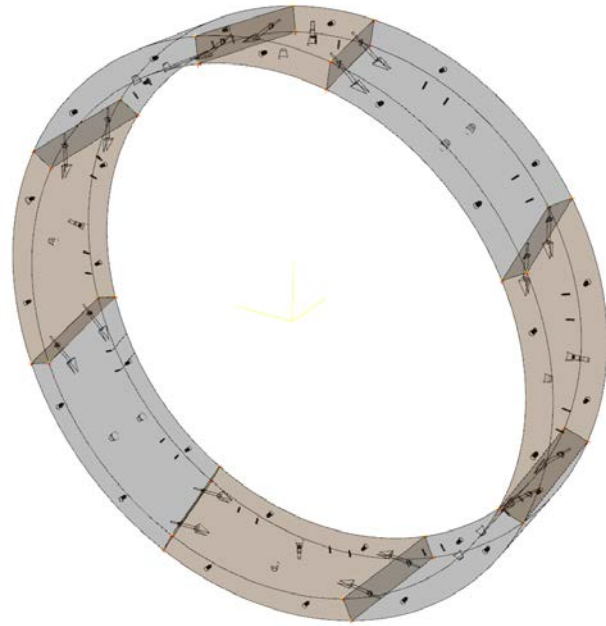
Figure 3: Cross section of the tunnel.
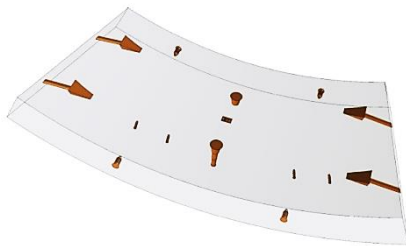

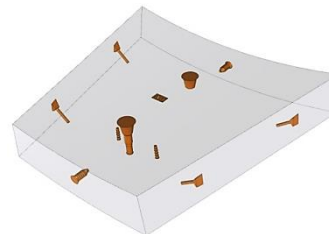Figure 4: Segmental lining 7+1.

Figure 5: Keystone E.

Figure 6: Keystone A.

3. SFRC TUNNEL LINING

Utilization of the SFRC for segmental tunnel lining promises potential advantages in comparison to the traditionally reinforced concrete (RC) structures - efficient manufacturing, lower risk of corrosion, less damage during transport, etc. Due to the lack of standards for SFRC structures design, the nonlinear finite element analysis is used and it is described in the following sections.

3.1 DESIGN OF SFRC SEGMENTS BY NONLINEAR ANALYSIS

Recent possibilities of the non-linear finite element analysis (NLFEA) offer a versatile tool for design of SFRC structures. Special numerical material models were developed for modelling SFRC (see [2]). These models take into account SFRC specifics such as shape of tensile softening branch, high toughness and ductility. 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.

4. INVERSE ANALYSIS OF TESTS – DETERMINATION OF MATERIAL CHARACTERISTICS

Bending tests of SFRC precast segment performed by Klokner Institute in Prague (see Figure 7 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 (see Figure 7 right) and failure mode of test and model.
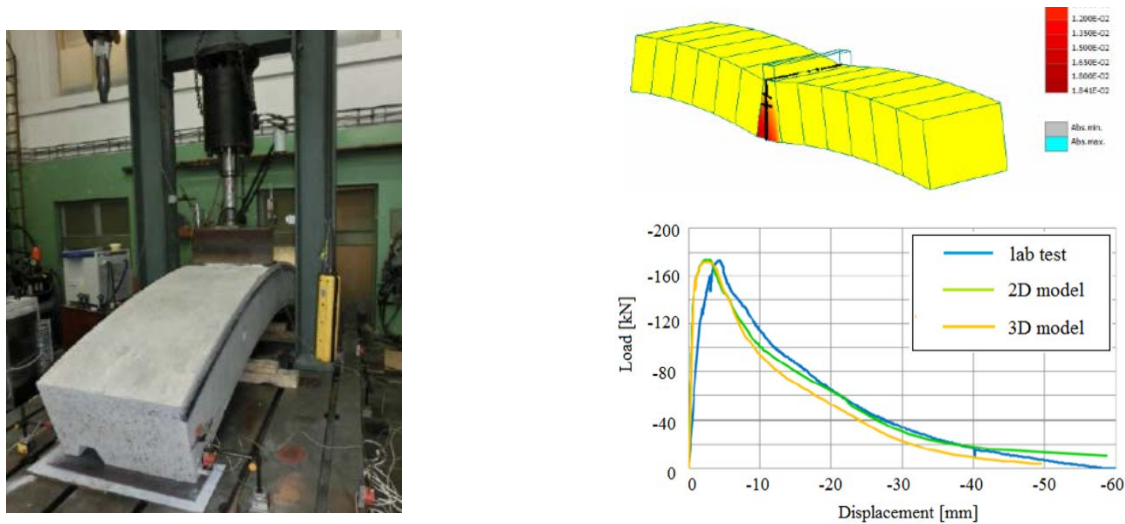

Figure 7: Identification of material parameters for SFRC model – bending test in lab (left), failure of numerical model (top right), load-displacement diagram of test and models (bottom right).

5. MODEL OF SEGMENT IN COMPRESSION (KEYSTONE A)

Material parameters obtained by inverse analysis are verified by analysis of keystone A which was subjected to compression test in the Klokner Institute. The keystone was loaded by concentrated pressure in the central part (see Figure 8) according to the conditions during installation of segments by TBM. Comparison of results and failure mode between the laboratory test and the model (see Figure 8) confirmed that the identified model is well suitable for modelling SFRC structures.
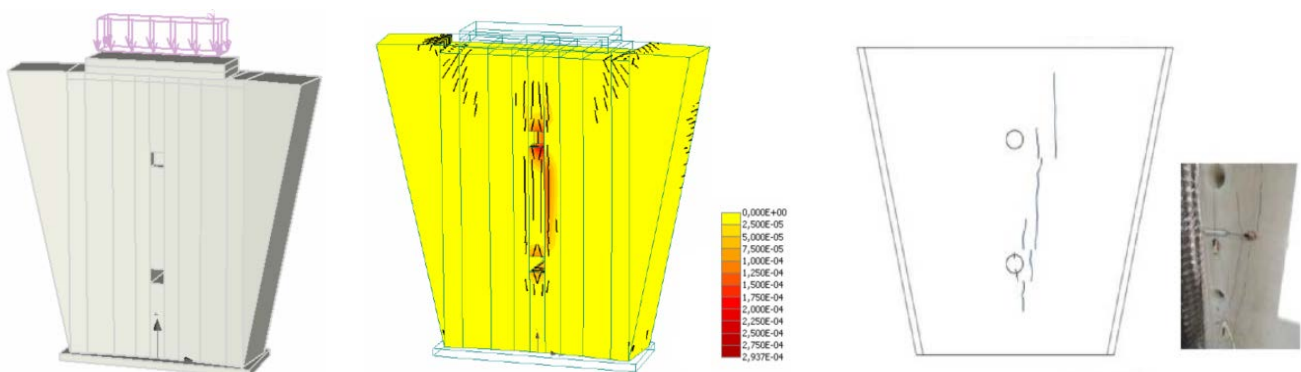

Figure 8: Model of keystone, crack pattern in the model and results of laboratory test.

6. DESIGN AND ASSESSMENT OF SFRC SEGMENTAL LINING

ATENA software was used for design and assessment of SFRC tunnel lining as well as for identification of material parameters. Segmental lining was assessed in four cross sections of Homolka massif and

Chlum massif. Nonlinear material models considering all relevant aspects of concrete behaviour in compression and tension were utilized for a realistic simulation of concrete structures. The tensile cracks are modelled by smeared crack concept with strain localization in continuous material. Crack formation is controlled by nonlinear fracture mechanics with softening characterized by fracture energy and tensile stress-strain curve.

Fracture-plastic material 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 10490 finite elements with 104 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.

6.1 SERVICEABILITY LIMIT STATE (SLS)

Crack width, strain, limitation of compressive stress and ovalization of the tunnel lining 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 (KS-1 to KS-4) of segmental lining.

From the evaluation of the ovalization the worst load case combination for the segmental lining was determined. Waterproof insulation is validated by relative displacement (W=0, 10, 15 mm) between segments according to producer of the insulation parts. Various curves in Figure 9 characterize insulation resistance against water column in terms of opening and relative displacement between segments.

The relative displacement in the contact between segments was modelled 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 10 shows displacement of contact elements in the model under loading.
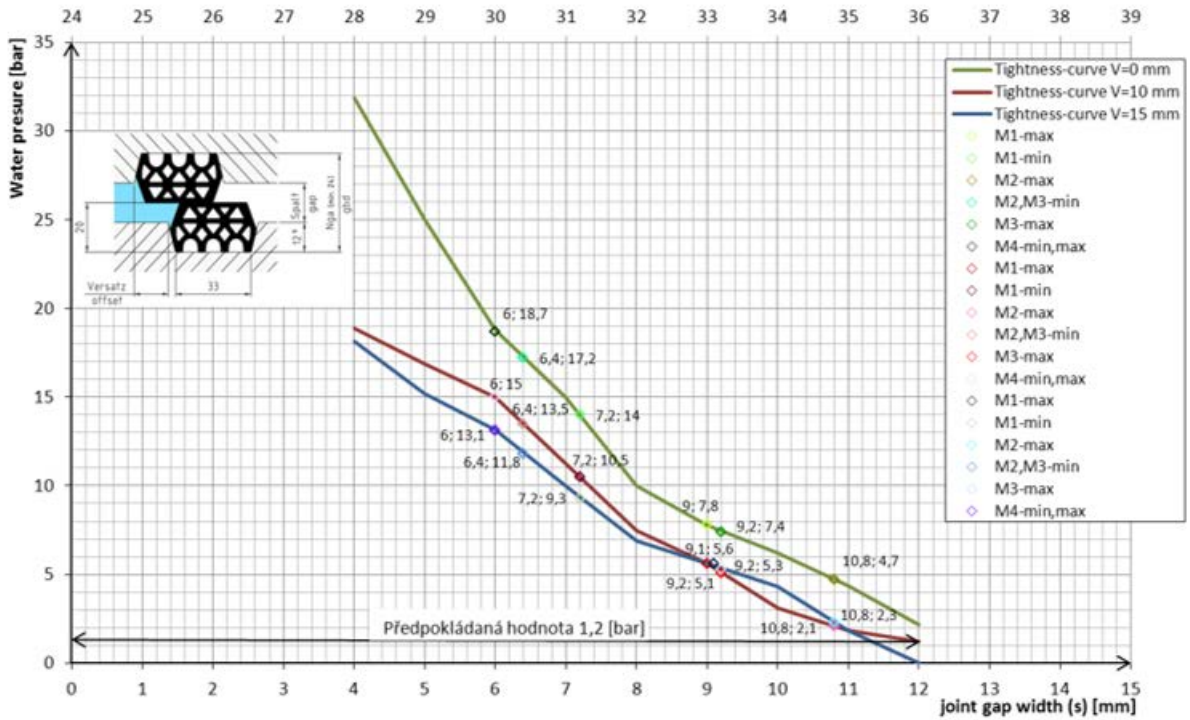
Figure 9: Resistance of waterproof insulation against water column.
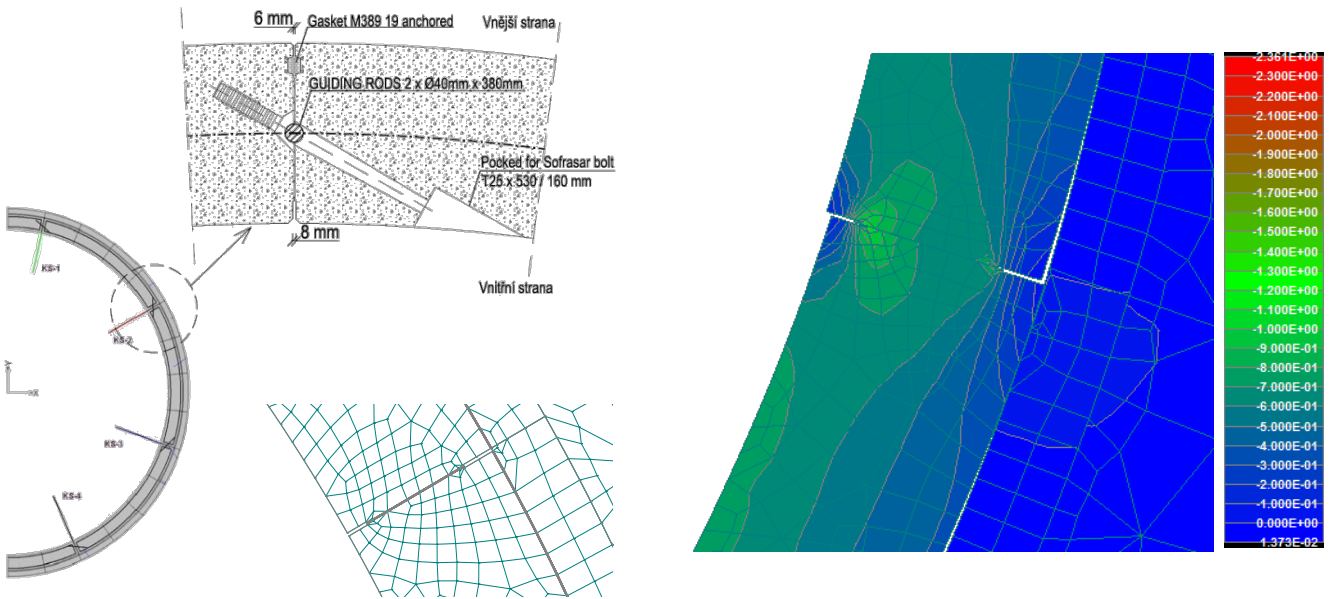

Figure 10: Contact detail (left), contact displacement in ATENA 2D model (right).

6.2 ULTIMATE LIMIT STATE (ULS)

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.

7. ASSESSMENT OF LOAD CASES: DEMOULDING, HANDLING AND STORAGE OF SEGMENTS

Due to the request to accelerate the manufacturing process simulations of load cases during segment production were performed. The crucial factor for demoulding the SFRC segment is increase of compressive strength over time. Limiting condition is development of the hydration heat in the structure which significantly influences shrinkage of concrete and consequent shrinkage cracking. Verification of the segment resistance in terms of demoulding, handling and storage was performed in four computational models: model for vacuum lifting, handling equipment and model for storage in interior and exterior.
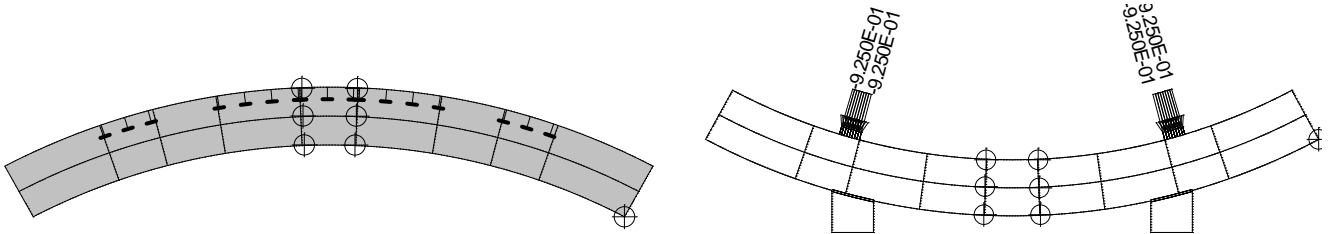

Figure 11: Model for vacuum lifting (left), model for segment storage (right).

All models were analysed for compressive strength (and corresponding tensile strength) at the age of 8, 10, 12 and 16 hours. Expected minimal compressive strength required for demoulding segments is 15 MPa for concrete class C45/55. Recommended value of compressive strength for segment storage is 19.2 MPa which corresponds to the age of 16 hours. Concrete stresses must be carefully controlled during demoulding, and appropriate handling methods such as vacuum lifting must be used in order to avoid segment bursting and spalling of concrete.

Figure 12: Storage of segments in interior (left), storage of segments in exterior (right).
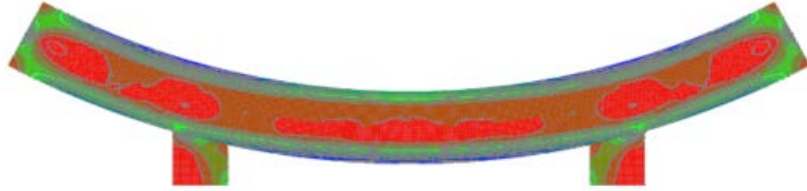

Figure 13: Demoulding of segment.

Figure 14: Results from the numerical simulation - tensile stress in the segment, max. stress 0.894 MPa.

8. CONCLUSION

Nonlinear computer simulation analysis was utilized for modelling of SFRC precast tunnel segments and design and assessment of the segmental tunnel lining.

Appropriate material characteristics for SFRC numerical model were obtained by inverse analysis from laboratory tests. These input parameters were verified on model of keystone for which the results of numerical simulation and laboratory test were compared. The approved models were then used in design of the structure in serviceability as well as ultimate limit states.

The suitability of the nonlinear finite element analysis for design and assessment of SFRC structures was already previously tested in design and realization of extension of the Prague Subway line A, and its applicability was confirmed here on another practical project.

9. ACKNOWLEDGEMENTS

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