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Application of Fiber - Reinforced Concrete in Tunnel Construction: Innovations and Challenges

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Abstract

The introduction of fibers into the testing of concrete mixtures, particularly in the post-elastic zone, induces positive changes ranging from mild to significant, depending on a variety of factors including the strength of the concrete matrix, type of fibers, elasticity modulus of the fibers, fiber strength, surface bonding characteristics of the fiber to the concrete matrix, fiber content, fiber orientation within the matrix, and the effects of aggregate size. The use of concrete combined with steel fibers contributes to the plastic behavior of this type of material, which is especially suitable for applications where traditional reinforcement is difficult to implement, such as in tunnel linings. Modern demands in the field of civil engineering continuously require the introduction of new technologies to achieve higher quality, more durable, and more economical materials. In this context, this paper presents the application of fiber-reinforced concrete for the construction of the primary substructure of tunnel structures. Before being used to create the primary support of the tunnel structure, experimental-theoretical analysis and modeling of the applied fiber-reinforced concrete was conducted. The main scientific contribution of this paper is the use of the obtained laboratory characteristics of cylindrical samples (the working σ-ε diagram of fiber-reinforced concrete) for the calculation of tunnel linings. A review of the research community shows that until now, it has not been possible to apply the working σ-ε diagram of fiber-reinforced concrete in a digital format, thus, from this perspective, the presented paper represents an innovation. Based on the presented analysis and additional analysis of the tunnel structure, it can be safely concluded that the differences between the two compared linings are within the domain of calculation error. The bearing capacities of the linings are close and the savings are reflected in the exclusion of the prefabricated reinforcement position, certainly in the case of economic justification of the use of fiber-reinforced tunnel lining.

Keywords

Tunnel lining, Fiber-reinforced concrete, Nonlinear analysis.

1 Introduction

1.1 Model Description and Input Data

A two-dimensional finite element model was developed to determine the displacement field, stress states, and plastic zones of both unsupported and supported excavation, as well as the effects on the tunnel lining. The model encompasses a sufficiently large portion of the surrounding ground to minimize the influence of boundary conditions on the calculation results within the tunnel zone. In the example presented, fixed boundary conditions are applied on all sides. Three-node finite elements were used for the modeling.

The primary stress state represents the stress conditions in the soil for the undisturbed state prior to tunnel excavation. If no specific measurements of the initial stress state have been conducted and no particular geological conditions exist, the vertical stress can be assumed as the weight of the overlying soil. The horizontal stress is then assumed to be a fraction of the vertical stress for an elastic solution. The ratio of horizontal to vertical stress, when determining the primary stress state, is defined using Poisson's ratio, ν, in the form:

$$\frac{\sigma h}{\sigma v} = \frac{\upsilon}{1-\upsilon} \tag{1}$$

During tunnel excavation, the primary stress state changes. This change is not a fixed value but a function of soil parameters, the stiffness and strength of the lining, and the time of its installation. The excavation is simulated using a step-by-step elimination procedure of finite elements defining the soil (a group of elements from element $m$to element n). The stresses in the eliminated elements are then integrated and applied as external loads.

Stresses in the surrounding materials, caused by stress redistribution during excavation, may exceed the allowable stress limits. In such cases, plastic deformation occurs. The difference between the allowable stress level and the actual stresses causes further redistribution in the surrounding material or the installed lining.

1.2 Model of Tunnel Structure

When selecting the tunnel structure model, the quality of the rock mass, the degree of variability, and the quality along the tunnel are taken into account. Construction technology and the height of the overburden also influence this choice. The cross-section is a complex horseshoe-shaped figure, consisting of a crown with an excavation radius of 5.85 m, a bench 2.00 m high, and a base vault that closes the entire contour. This type of tunnel extends through the geotechnical environment A of the tunnel, with characteristics provided in the following table 1.

Table 1. Characteristics of the Geotechnical Environment.

Physical and Mechanical Properties of the Material	Geotechnical Environment			
	A: Diabase Hornfels Formation – Hornfels	**B:** Diabase Hornfels Formation – Clays	**C:** Deluvial–Eluvial Cover	**D:** Limestones – Zone of Surface Alteration
vp(km/s)	1,80-2,37	3,78	0,60	2,40
vs (km/s)	1 150	1,75		1 300
γ(kN/m3)	25	24		24
μ	0,35	0,34		0,35
Edyn (Mpa)	5 200	22 600		5 800
G (Mpa)	3 300	9 000		3 700
K (Mpa)	9 500	21 000		10 500
Est (Mpa)	1 600 - 2 200	4 800 – 6 300		2 000 - 2 900
D (Mpa)	400 - 700	1 300 – 2 2 0		600 - 1 100

- Coulomb–Mohr Failure Criterion

Model B

For *Coulomb-Mohr*-a:

Geotechnical Data	Diabase Hornfels Formation – Predominantly Hornfels
Class of the Tunnel	Model B
γ (kN/m^3)	25
φ (^{o})	25
E (MPa)	2000
ν (-)	0.28
c (MPa)	0.20
D (MPa)	120

2 Experimental Program and Applied Methodology

2.1 Numerical Models of Excavation Support Using Reinforced Concrete (RC) and Using Fiber-Reinforced Concrete (FRC)

For the numerical investigation comparing the behavior of excavation support, a traffic tunnel model was adopted. The study presents a comparison of the excavation contour support performance during excavation using:

- Conventional concrete of class 25/30 reinforced with a double-layer steel mesh
- Fiber-reinforced concrete of class 30/38.7, reinforced with hooked-end steel fibers with a shape factor of L/D = 50/0.75 and a fiber content of 2% by volume of the total concrete mixture.

The objective of this numerical analysis was to demonstrate the behavior of the rock mass around the excavation in the case of using fiber-reinforced concrete with characteristics L/D = 50/0.75, with emphasis on the significantly increased toughness of this concrete, while all other parameters remain the same for both cases: geotechnical characteristics of the rock mass, loads during staged excavation, and compressive strength of the base reinforced concrete (RC) material. Passive anchors were not installed, as they are not of interest for this study.

The reinforced concrete lining is modeled as a beam element because the reinforcement enables it to carry normal forces, shear forces, and bending moments. The allowable stresses are adopted as follows, according to the current regulations:

- Concrete class C25/30, i.e., 30 MPa
- Allowable bending stress: 12 MPa (safety factor 2.50)
- Allowable tensile stress without cracking: 1.5 MPa (safety factor 20)

The basis for comparing the two linings is the operational principle of the PHASE2 software package for the analysis of tunnel structures. This software requires peak and residual values as input data for both the rock and the RC lining, which is standard when applying the Failure Theory.

Therefore, considering a minimum safety factor of 1.50 for compressive stresses and 10 for tensile stresses for the limit states used to assess and compare the load-bearing capacity of RC and fiber-reinforced concrete (FRC) linings, the following data are adopted for the RC lining:

- Peak compressive stress: 30 MPa
- Residual compressive stress: 5 MPa
- Peak tensile stress: 5 MPa
- Residual tensile stress: 1 MPa

Until now, no software has been capable of accepting defined working σ–ε diagrams of concrete in digital form as input data for further structural behavior analysis. This capability is crucial in the case of fiber-reinforced concrete (FRC) due to its drastically enhanced toughness after reaching peak strength.

One of the significant contributions of this study is the use of a laboratory-derived working σ–ε diagram of fiber-reinforced concrete in digital form for the calculation of tunnel linings. The presented method of modeling FRC is the only way to directly compare conventional reinforced concrete (RC) and FRC models. The comparison between the two proposed linings is made possible by the increased tensile strength of fiber-reinforced concrete, in this case achieved using steel fibers.

Laboratory tests show that the compressive strength of fiber-reinforced concrete increased by approximately 5% compared to standard samples (without fibers), while the tensile strength increased by up to 50%. These laboratory tests apply to a concrete age of 28 days, after which a slight reduction in both compressive and tensile strength is observed.

It should be noted that this study does not address long-term monitoring of changes in compressive and tensile strengths (beyond 28 days), which may be highly relevant in cases such as work

interruptions. This is particularly pertinent to underground works over extended periods due to factors such as financial constraints or abandonment of the project by the contractor for unforeseen reasons.
For the purposes of this study, the following input data for FRC are adopted:

- Peak compressive stress: 38.7 MPa
- Residual compressive stress: 6.5 MPa
- Peak tensile stress: 7.5 MPa
- Residual tensile stress: 1.5 MPa

The RC model and the FRC model share identical geometry, surrounding model mesh, and geotechnical properties of the environment and rock mass, as adopted from the tunnel construction documentation.

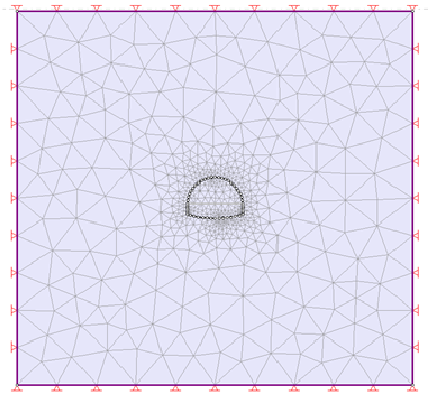
3 Results and Discussion

Graphical representations of the results are generated for both models to allow for comparison.

3.1 Numerical model

The geotechnical characteristics of the surrounding rock mass are:

Material Properties

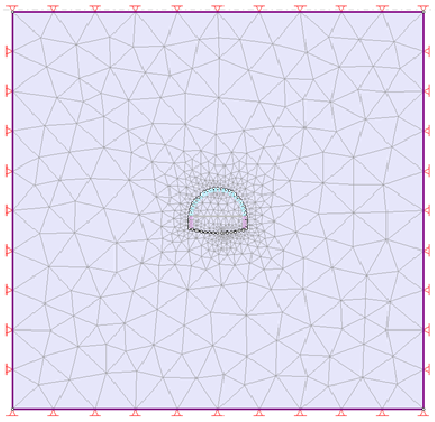


Material: Material 1
Initial element loading field stress & body force
Unit weight 0.025 MN/m3
Elastic type isotropic
Young's modulus 2000 MPa
Poisson's ratio 0.28
Failure criterion Mohr-Coulomb
Tensile strength 0 MPa
Peak friction angle 25 degrees
Peak cohesion 0.2 MPa
Material type Plastic
Dilation Angle 0 degrees
Residual Friction Angle 25 degrees
Residual Cohesion 0.2 MPa
Piezo to use None

Fig. 1 Numerical model.

3.2 Model with Reinforced Concrete (RC)

The numerical model with inserted 25cm thick concrete lining of class C25/30, reinforced with two layers of Q131 reinforcement mesh, is shown in the figure 2. The characteristics of the concrete lining in the model are:



Liner Properties
Liner: Liner 1
Liner Type Standard Beam
Formulation Timoshenko
Thickness 0.25 m
Elastic Properties
Young's modulus 30000 MPa
Poisson's ratio 0.2
Liner: Liner 2
Liner Type Standard Beam
Formulation Timoshenko
Thickness 0.25 m
Elastic Properties
Young's modulus 30000 MPa
Poisson's ratio 0.2

Fig. 2 Model with Reinforced Concrete Lining.

The stress-strain diagram for both phases of tunnel excavation (σ_1, σ_3) is shown in Figures 3 to 8.

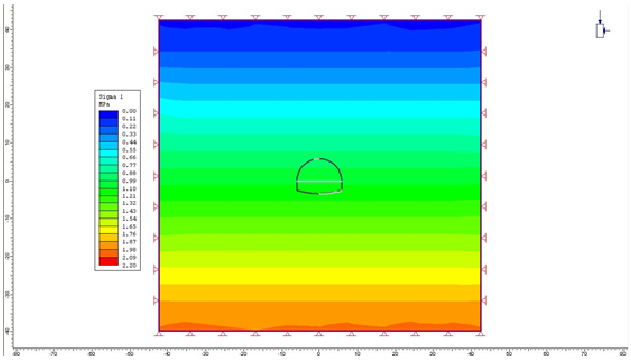


Fig. . σ_1 - Primary state –RC

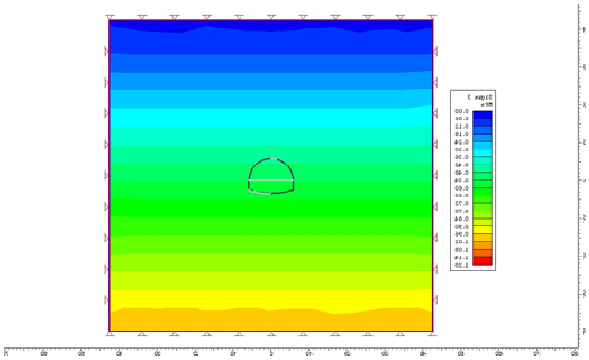


Fig. 4 σ_3 - Primary state – RC.

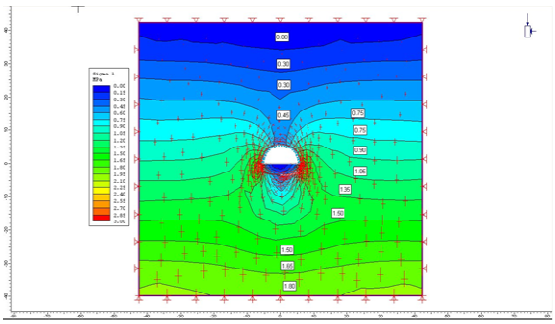


Fig. 5 σ_1-First phase of tunnel excavation- RC.

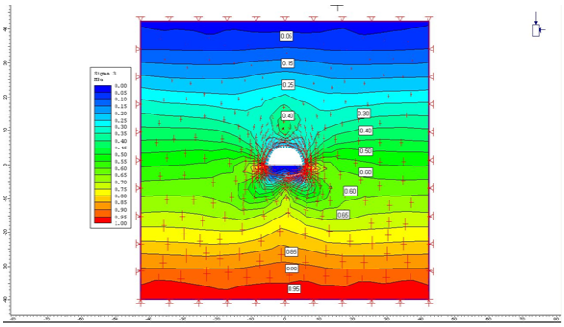


Fig. 6 σ_3 - First phase of tunnel excavation- RC.

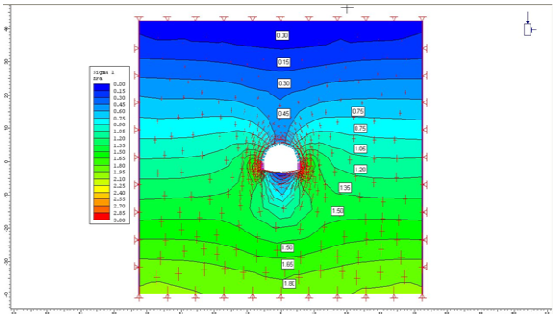


Fig. 7 σ_1 - Excavation of the entire tunnel contour- RC.

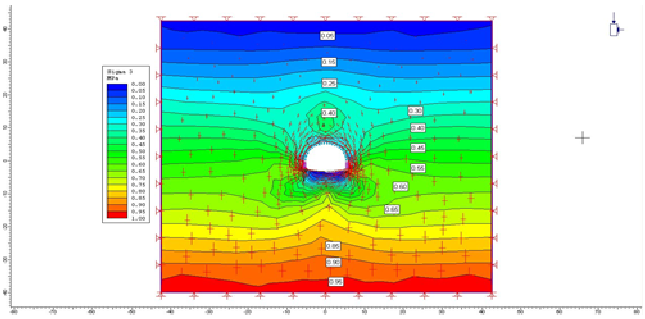


Fig. 8 σ_3 - Excavation of the entire tunnel contour- RC.

3.3 Model with Fiber-Reinforced Concrete Lining (FRC), L/D = 50/0.75, 2% Steel Fibers

Numerical model with inserted 25 cm thick fiber-reinforced concrete lining of class 37.8 MPa as shown in the figure 9.

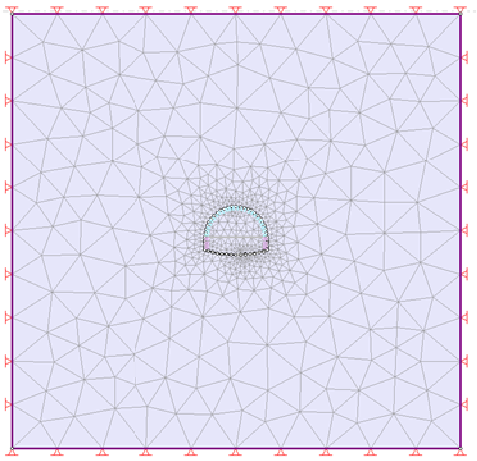


Fig. 9 Model with Fiber-Reinforced Concrete.

The characteristics of the fiber-reinforced concrete lining in the model are as previously stated:

- Peak compressive stress: 38.7 MPa
- Residual compressive stress: 6.5 MPa
- Peak tensile stress: 7.5 MPa
- Residual tensile stress: 1.5 MPa

The stress-strain diagram for both phases of tunnel excavation (σ_1, σ_3) is shown in Figures 10 to 13.

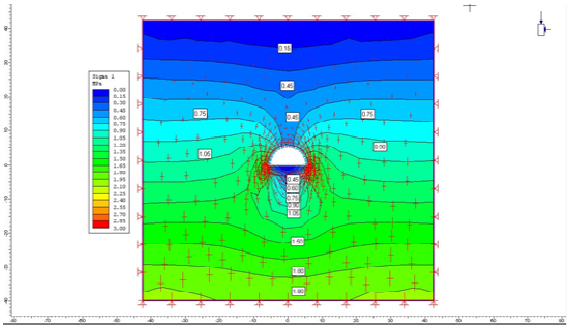


Fig. 10 $\boldsymbol{\sigma_1}$ -First phase of tunnel excavation – FRC.

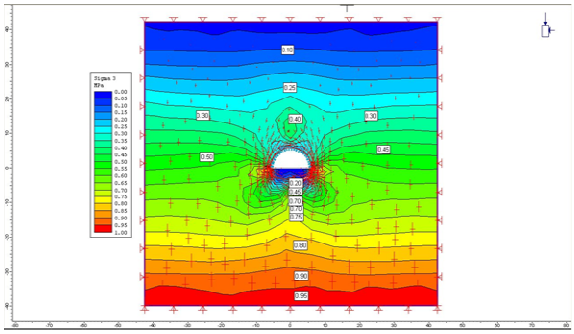


Fig. 11 $\boldsymbol{\sigma_3}$ - First phase of tunnel excavation – FRC.

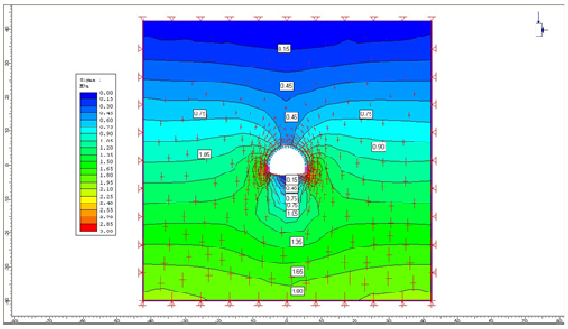


Fig. 1 $\boldsymbol{\sigma_1}$ - Excavation of the entire tunnel contour – FRC.

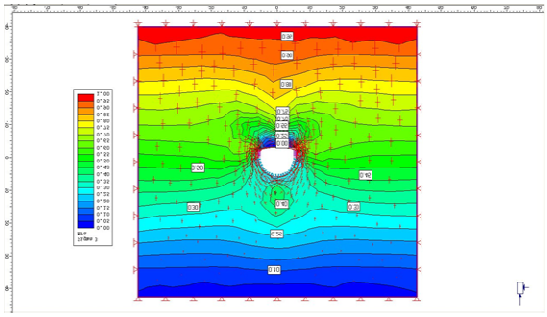


Fig. 13 $\boldsymbol{\sigma_3}$ - Excavation of the entire tunnel contour – FRC.

3.4 Supplementary Analysis

3.4.1 Formation of input files

The input files are the final files for this study, corresponding to the analyzed type of traffic tunnel, which has been cleared of anchors. The same data are provided for the lining for both conventional reinforced concrete (RC) and fiber-reinforced concrete (FRC):

- For the lining without fibers:
  - ❖ Peak compressive stress: 30 MPa
  - ❖ Residual compressive stress: 5 MPa
  - ❖ Peak tensile stress: 5 MPa
  - ❖ Residual tensile stress: 1 MPa
- For the lining with fibers:
  - ❖ Peak compressive stress: 38.7 MPa
  - ❖ Residual compressive stress: 6.5 MPa
  - ❖ Peak tensile stress: 7.5 MPa
  - ❖ Residual tensile stress: 1.5 MPa

The lining thickness varies from 25 cm to 20 cm and 15 cm, depending on the characteristics of the rock mass along the considered section.

In this study, diagrams of U_tot (total displacements) are provided for the two excavation stages. The purpose of this supplementary analysis was to compare displacements for both cases, i.e., conventional reinforced concrete (RC) and fiber-reinforced concrete (FRC), at different excavation stages, and to illustrate the magnitude of displacements for each case. This is supported by the superior mechanical performance of FRC, particularly its pronounced toughness, which allows fiber-reinforced shotcrete to undergo plastic deformation for a longer period.

Input files for PHASE2V6 carry labels:

F B_modelA2_RC_15_PH2v6

B_modelA2_RC_20_PH2v6

B_modelA2_RC_25_PH2v6

or FRC:

B_modelA2_FRC_15_PH2v6

B_modelA2_FRC_20_PH2v6

B_modelA2_FRC_25_PH2v6

Data for max U_tot (maximum displacements) for the models processed in PHASE2v6:

D	maxUtot	
	1. phase	2. phase
RC		
15	0.00661257	0.00607221
20	0.00661257	0.00605811
25	0.00667319	0.00604121
FRC		
15	0.00654235	0.00608391
20	0.00661257	0.00605811
25	0.00667319	0.00604121

Based on the presented analysis and the supplementary analysis of the tunnel structure, it can be confidently concluded that the differences between the two compared linings are within the margin of computational error. The load-bearing capacities of the linings are similar, and the savings are reflected in the elimination of the placement of assembly reinforcement.

4 Conclusion

The use of fiber-reinforced concrete with steel fibers, hooked at the ends, and a shape factor of L/D = 50/0.75, at a dosage of 2% by mass of the concrete, yields excellent results in the structural analysis of the tunnel lining. In this case, the total displacements of the fiber-reinforced tunnel lining coincide with the total displacements of the conventional reinforced concrete lining. This demonstrates the feasibility of using fiber-reinforced concrete in the design of underground structures as a substitute for conventional reinforced concrete linings, with the important caveat that the production technology of fiber-reinforced concrete and the homogeneity of the concrete mixture are key factors for achieving the favorable performance and properties of the tested fiber-reinforced composite.

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