Crack resistance estimation of fibre reinforced tunnel linings constructed by conventional method in rocks

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Abstract. The article represents crack control research results of horseshoe-shaped fibre reinforced concrete tunnel linings which are constructed by conventional tunneling method on a full cross-section in rocks. Based on linear fracture mechanics an alternative method for estimation of the crack resistance for such kind of linings is proposed. The research was carried out by using the finite element method supported with experiment planning method.

In recent decades, Russia has experienced intensive development of transport infrastructure, which requires the expansion of the road network and the construction of new transport tunnels, often constructed in the mountainous regions of Siberia, the Urals, and the Caucasus. The construction of tunnels belonging to the structures of the highest category of responsibility in mountain conditions imposes special requirements on the materials used in their construction work.

In particular, significantly increased the using of fibre reinforced concrete (FRC) in construction of tunnels in rocks, where the FRC is used not only for temporary support, but also for construction of load-bearing linings, designed for the entire period of tunnel operation.

In the latter case, it can be used for the manufacture of precast FRC segmental lining for shield tunneling [1,2,3], or for the cast-in-place FRC linings and shotcrete linings [3].

Worldwide experience of using FRC shows a significant reduction of construction period and building cost, increase of operational reliability and durability of structures being constructed (figure 1).

In comparison with FRC plain concrete has enough compression strength but low tensile strength. Using of structural fibre (steel or synthetic) evenly distributed in concrete matrix increases the tensile strength of concrete, which provides, unlike concrete, a stable propagation of cracks.

In addition, having a higher tensile strength, FRC allows to significantly reduce or even avoid using of rebars, especially for linings in rock conditions.

The research results [4,5] allowed to conclude that FRC deformation behavior under load similar to quasi-solid, quasi-homogeneous, elastic material. The comparison of results of physical and numerical modeling of crack propagation in a circular FRC lining segment showed (figure 2) their good convergence (within the range of 8-12%).

Research results also showed that the crack resistance of the circular lining segment is determined by a single crack formed in the arch apex, where the maximum tensile stresses are observed. This
crack can spread both steadily and unsteadily. The steady propagation of the crack means that it can stop at some point and its continued growth is possible only with a further increase of applied load.

![Figure 1. An example of the lining of a transport tunnel. The operated Severomuysky tunnel.](image)

All of the above made it possible to conclude that the process of crack formation in FRC can be studied by linear fracture mechanics methods [5,6,7,8], and alternative approach for crack resistance estimation of FRC linings can be developed using it.

Linear fracture mechanics considers the process of crack formation in an elastic body and the patterns of its propagation. Its appearance was due to the fact that the dependences of the theory of elasticity do not allow us to analyze the process of crack propagation in an elastic medium, since in this case a singular region is formed at the crack tip, in which the values of the stress components tend to infinity, which does not allow us to use them as a criterion for crack growth.

For this purpose, the concept of stress intensity coefficients \( K_I, K_{II}, K_{III} \) is introduced in fracture mechanics [9], which characterize the intensity of stress distribution in the region around the crack mouth under conditions of normal rupture (pure tension), pure shear, and complex stress state (tension + shear), respectively [10].

In [4,5] showed that in the circular linings conditions of normal rupture are realized in the arch apex, where they reach their maximum. This fact indicates that in this area microcrack may occur when load will apply. In FRC usually, the factor which cause its appearance is the presence of microcracks along the contact of fibre or aggregate with cement matrix.

Since the conditions of normal rupture are realized in the cross section, macro-crack will move in its plane, normal to the action of tensile stresses. The condition for start and stop crack propagation, in this case, is determined only by the value of the intensity coefficient \( K_I \). The crack movement will start and stop when the corresponding conditions are met:

\[
K_I \geq K_{Ic} \text{ and } K_I \leq K_{Ic}
\] (1)
Figure 2. (a) Testing of circular FRC lining segment. (b) Numerical simulation of testing of circular FRC lining segment.

The value of $K_{IC}$ is a constant mechanical characteristic of the material, in that case – FRC, and it has to be determined experimentally [5]. The value of stress intensity coefficient $K_i$ in the lining can be determined by the method described in [7] for eccentric compressed element of small curvature, in accordance with the scheme shown in figure 3, using the formula:

$$K_i = \sigma^0 \sqrt{f_1(\lambda_0)} + \Delta \sigma \sqrt{f_2(\lambda_0)}$$  \hspace{1cm} (2)

in which $\lambda_0$ is the ratio of initial crack length to the lining thickness; $\sigma^0$-stresses at the crack mouth; $\Delta \sigma$ – the stress difference at the mouth of the propagated and the initial cracks; $l_0$ – the initial crack length, assumed to be equal to the fibre used average length; $f_1(\lambda_0), f_2(\lambda_0)$ are the table functions given in [7].
Using expressions (1) and (2), studies of the crack resistance of FRC lining of horseshoe-shaped (Figure 1), constructed by the conventional tunneling method, were performed, taking into account the excavation of rock to the full cross-section of the tunnel.

To determine the cracks areas in lining, it is necessary to understand the stress-strain state of lining interacting with rock massif.

Based on the analysis of tunnel linings behavior in rocks and previously performed studies [8, 9], the main independent factors affecting the crack resistance of linings were determined.

The interaction of rock mass and tunnel lining was carried out within the 2D conditions (plain strain) using the finite element method provided by special geotechnical software ZSoil.PC 2D/3D 2020 [11].

Processing of the calculation results and obtaining on their basis parametric equations (regression equations) connecting the desired response function with the selected independent factors was carried out using factor analysis based on the theory of experiment planning [12], which allows to obtain these equations, minimizing the required number of experiments, by constructing an experiment planning matrix.

\[ \frac{E_c}{E_{ef}} \] - the ratio of the tunnel lining concrete elastic modulus to rock mass effective modulus of deformation, dimensionless value;

\[ H \] – depth of the tunnel arch apex, metres;

\[ b/h \] – the ratio of the width size of tunnel excavation to its height, dimensionless value;

\[ \lambda \] - is the coefficient of lateral ground pressure, dimensionless value.

The rock massif was modeled as a continuous homogeneous medium with the effective modulus of deformation, taking into account the presence of cracks (smeared cracks) [13]. The depth of the tunnel, the shape and dimensions of the excavated opening were taken on the basis of experience in the construction of transport tunnels in fractured rocks [14]. The lateral pressure coefficient was assumed based on the results of previously performed studies [15,16]. Table 1 shows the values of factors and the limits of their variation.

The result of each calculation of stress distribution in the «tunnel – rock massif» system allows to determine the distribution of internal forces in the lining. On the basis of this analysis, the sections

**Figure 3.** Scheme for calculating the stress intensity coefficient at the tip of a crack of normal separation in an eccentric compressed element.
where cracks may appear are determined, which allows us to proceed to analysis of the process of their propagation.

### Table 1. Natural values of factors and the range of variation

| Factors | The range of variation | Average value |
|---------|------------------------|---------------|
| $E_c/E_{ef}$ | 8 - 32 | 20 |
| $H$ | 30 - 150 | 90 |
| $b/h$ | 0.5 – 2.0 | 1.25 |
| $\lambda$ | 0.2 – 0.9 | 0.55 |

In the linings of transport tunnels of a horseshoe-shape built by conventional tunneling method to a full cross-section in rocks, the appearance of cracks is possible in the crown, walls and invert, where the maximum tensile stresses were observed, i.e., the conditions of normal rupture are realized.

In these sections, the initial cracks were modeled in the FEM mesh on the side of the inner or outer surface of the lining at the points of maximum tension, the lengths of which were determined by the average length of fibre – 50 mm. Using equation (2), the stress intensity coefficient $K_I$ was calculated at the mouth of each crack, and the nature of their propagation (steady or unsteady, i.e., leading to the destruction of lining) was determined by equation (1).

The analysis showed that with the observed stress distribution in the lining, cracks in its arch and invert do not develop, and cracks in the walls, due to symmetry, distributed symmetrically and stably, being the only factor that determines the crack resistance of lining. In the course of study, it was found that there are two possible ways for propagation of cracks formed in the walls. In first case, the initial crack does not propagate (Figure 4) or propagates steadily with stopping at a certain depth (Figure 5). In second case, the crack can advance to a depth which not allowed according to the requirement for remaining minimum thickness for cast-in-place lining (SP 120-13330-2012. "Metro"). In such case it may be necessary to change the composition of the FRC or use conventional reinforcement. Unstable crack propagation was not observed during the research.

According to results of the research using factor analysis, was determined factor dependences of the stress intensity coefficient $K_I$ (3) and internal forces $M$ (4), $N$ (5) on the selected factors in the section of lining where the crack can advance were obtained. These dependences allows to estimate the crack resistance of horseshoe-shape FRC linings for full cross-section conventional tunneling method in different combinations of the values of selected factors inside described limits.

All of the above allows us to conclude that the proposed calculation method truly reflects the process of crack propagation in the horseshoe-shape FRC linings, which makes it possible to use it at the preliminary design stages when fibre reinforced concrete tunnel lining constructed to the full cross-section.

It should be noted that the change in the method of the tunnel excavation will affect the distribution of stresses in the lining and, accordingly, the formation and propagation of cracks in it. The study of these processes requires additional research.

Regression equations for calculating the stress intensity coefficient ($K_I$) in the section of the wall lining:

$$ K_{int} = -340.06 + 32.97 \times \frac{E_c}{E_{ef}} + 5.97 \times H - 39.30 \times \frac{b}{h} + 376.03 \times \lambda $$  \hspace{1cm}  (3)

Regression equations for calculating the bending moment ($M$) in the section of the wall lining:

$$ M = -540.77 + 19.61 \times \frac{E_c}{E_{ef}} + 3.71 \times H + 384.46 \times \frac{b}{h} - 345.65 \times \lambda $$  \hspace{1cm}  (4)
Regression equations for calculating the longitudinal force ($N$) in the section of the wall lining:

$$N = -1862.83 + 33.46 \times \frac{E_c}{E_{ef}} + 11.75 \times H + 1317.86 \times \frac{b}{h} - 768.73 \times \lambda$$  \hspace{1cm} (5)
Analysis of the results of conducted research allows to form the following conclusions:

1. The research confirm the possibility of using linear fracture mechanics for analysis of crack propagation in FRC tunnel lining of the horseshoe-shape.
2. The distribution of stresses in the FRC lining of a tunnel constructed by conventional tunneling method, and therefore its crack resistance, is affected by the sequence of opening, which requires additional similar research for other sequences or methods of tunnel excavation.

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