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Research Article

Theoretical Analysis of Reinforcement Tunnel Lining Corrosion

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Abstract: The main cause of ageing damage in reinforced concrete structures is reinforcement corrosion. Damage can be detected visually as coincident cracks along the reinforcement bar, which are significant of both reduction of the re-bar, cross-section and loss of bond strength for reinforced concrete. The reinforced concrete is one of the most widely used engineering materials as final lining of tunnels. The corrosion is common durability problems that have significant effect on the tunnel performance. This study intends to analysis reinforcement concrete corrosion at the tunnel lining by applying temperature expansion theory on steel through numerical simulation process, with expansive force effect. The thickness of concrete cover and the diameter of steel bar have an impact on the stress for reinforcement concrete during propagation of corrosion process. The corrosion cracks appear at the corner of a tunnel lining then in invert and vault because the maximum stress will be in the corner then in invert and vault. The internal force in the concrete lining changes differently when the corrosion rate change.

Keywords: Finite element analysis, R.C corrosion, second tunnel lining corrosion

INTRODUCTION

Tunnel structures are becoming of increasing importance for the infrastructure. Most of these tunnel structures are constructed from steel reinforced concrete with a design service life in excess of 100 years. The corrosion of reinforcement bar is considered as the most prevalent mode of deterioration that affecting on the serviceability, safety and structural integrity of tunnel. Both the inner and outer wall surface of tunnel structures exposed to aggressive exposure conditions. The inner concrete surface is subjected to chloride-laden splash and spray originating from the abundant that use of de-icing salts during winter periods and an increased level of atmospheric carbon dioxide resulting from exhaust gases. Normally, the outer concrete surface is continuously exposed to a wet environment especially, in coastal areas. The external exposure condition is aggressive as both surface water and ground water that may contain significant amounts of chloride (Gulikers, 2001).

In view of the great economic importance of tunnel structures, the severe environmental exposure conditions, the limited possibilities for inspection, maintenance and repair during service, as well as factors related to safety and serviceability, an urgent need has emerged to critically evaluate the process of reinforcement corrosion in a tunnel environment.

The splitting process of concrete cover due to the volume expansion action of corrosion products has been investigated by use of inner expanding band. The finite element analysis is proposed to simulate the second corroded tunnel lining model by used ANSYS software. The main idea of model is used the temperature theory to simulate the corrosion on second tunnel lining.

LITERATURE REVIEW

Bazant (1979) presented an analytical model for predicting the time to cover cracking. His theory depends on the reinforcement diameter cover thickness, the tensile strength of concrete, the corrosion rate and the corrosion products density. Dagher and Kulendran (1992) are considered the formation of smeared cracks that caused by the exertion of uniform pressure from the corrosion products at the reinforcement concrete's interface. They are found that a radial expansion of 0.008 mm is sufficient to cause degradation in concrete bridge decks. Molina *et al*. (1993) used a smeared crack model with the finite element analysis of cover cracking that due to reinforcement corrosion. The corrosion of a steel element is modeled by presuming a linear variation of the material properties from those of steel to those of rust. The mechanical properties of rust nearly resemble (Molina *et al*., 1993). The analysis is

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based on the experiments of Andrade *et al*. (1993), where the thickness of the concrete cover is 1.25 and 1.9 times the reinforcement diameter. The result is found that a corrosion penetration of 0.02 mm was sufficient to initiate a surface crack in the specimens (Molina *et al*., 1993). Noghabai (1996) adopted an analytical model for the splitting capacity of a thick-walled concrete ring subjected to an inner pressure based on nonlinear fracture mechanics. Based on field and laboratory data, Morinaga (1989) suggested an empirical equation for predicting the time to cover cracking without reference to the evolution of the damage zone. His empirical equation accounts for the time to cover cracking as a function of the corrosion rate, concrete cover thickness and reinforcing diameter. A close scrutiny of the literature (Liu and Weyers, 1998; Bhargava *et al*., 2006) reveals that the cover cracking predicted by Morinaga's model is much shorter than the experimentally observed values. Pantazopoulou and Papoulia (2001) are developed an analytical model to investigate how corrosion products cause concrete cover cracking, which endangers the service life of RC structures. The study assumed that the rebar and the corrosion products behave like a rigid material. Moreover, the corrosion production is simply modeled by imposing a radial displacement on the inner surface of concrete. They investigated the effects of cover thickness, material properties of concrete and the rate of rust accumulation on the time of cover cracking. However, further investigations in this field have revealed that the consideration of the appropriate mechanical behavior of corrosion products strongly affects the predicted results (Kiani, 2002). Lundgren (2002) in an effort to study rebar pull-out, presented a reasonable way to model the effect of corrosion on the bond between the corroded reinforcement and concrete (Lundgren, 2002). Lundgren (2002) employed finite element analysis and assumed that rust behaves like granular materials, in accordance with the experimental tests of Andrade *et al*. (1993), Al-Sulaimani *et al*. (1990), Cabrera and Ghoddoussi (1992) and Ghandehari *et al*. (2000). In another work, Lundgren (2002) used the previously developed model of rust together with a bond mechanism model to explore the effect of uniform and localized corrosion on RC beams with corroded reinforcements. Lundgren (2002) pointed out that the model could predict the decrease of the bond when splitting of the concrete occurs. It was emphasized that axial symmetric analysis appears to be a satisfactory level of modeling when a study of concrete cover cracking due to uniform corrosion is of concern. However, three dimensional models should be used if localized corrosion is to be studied (Lundgren, 2002).

In the durability study of lining concrete of Jiao Zhou Bay subsea tunnel, through carrying chloride ion diffusion test in a number of concrete blocks with different concrete mix ratios. The finding is concluded that the tests results show that critical compressive load apparently accelerates the carbonation and deteriorates the anti-permeability of concrete. Under the combined action of critical compressive load and carbonation, the durability of lining concrete decreases (Chen *et al*., 2010).

THEORETICAL ANALYSIS

The theoretical model assumes the uniform corrosion around steel bar, which causes uniform expensive stress around the same bar. The relationship between volume expansion for steel corrosion in reinforcement concrete and temperature expansion for same steel bar is divided into stages:

- **Temperature expansion volume computation:** Any changing with reinforcement concrete temperature is caused shrinkage in the steel bar, which products equal pressure in the concrete. The changing of one temperature unite produced one unite of volume changing. The temperature volume relationship is calculated by thermal volume expansion as follows:

Thermal volume-expansion coefficient (α_v):

$$\alpha_v = \Delta V / (V \times \Delta T) \tag{1}$$

If the volume changes linearity:

$$V = a\ b\ c \tag{2}$$

Then:

$$\alpha_v = \Delta(abc) / (abc \times \Delta T) \tag{3}$$

$$\alpha_v = (\frac{\Delta a}{a \Delta T}) + (\frac{\Delta b}{b \Delta T}) + (\frac{\Delta c}{c \Delta T}) \tag{4}$$

The thermal expansion coefficient:

$$\alpha = (\frac{\Delta a}{a \Delta T}), \alpha = (\frac{\Delta b}{b \Delta T}), \alpha = (\frac{\Delta c}{c \Delta T})$$

Then

$$\alpha_v = 3a \tag{5}$$

Therefore temperature quantity changing will express as below:

$$V_t = V_0(1 + 3\alpha \Delta T) \tag{6}$$

where,

V: Volume

The differentially changing temperature and volume is infinite small while in the high temperature the thermal-expansion will be not constant. Therefore the max temperature linear expansion will be 1.2 * 10-5/cwo (GB50010-2002).

- **Steel bar corrosion volume expanding computation:** The corrosion volume is calculated as following:

$$\eta = \frac{w_o - w_\eta}{w_o} = \frac{2\pi R_o \delta_o L_o \gamma}{\pi R^2 L \gamma} = \frac{2\delta}{R} \tag{7}$$

where,
n : Corrosion rate
W_o : Steel bar weight
Wn : Steel bar weight after corrosion,
R : Bar radius
L : Bar length
δ : Corrosion penetration

When Corrosion volume rate increased:

T: Temperature

$$\Delta V_\eta = 2\pi R \times \delta \times L(n-1) \tag{8}$$

Temperature expansional volume:

$$V_t = V_o(1 + 3\alpha\Delta T) \tag{9}$$

When Temperature expansional volume rate increased:

$$\Delta V_t = V_T - V_o = V_o(1+3\alpha\Delta T) - V_o = 3\alpha\Delta T V_o = 3\alpha\Delta T V_o = 3\alpha\Delta T\pi r^2 L \tag{10}$$

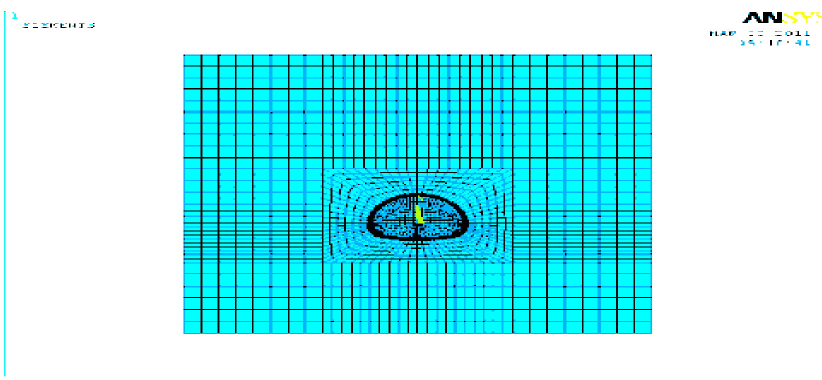
When : $\Delta V_t = \Delta V_n$ then:

$$\Delta V_\eta = \Delta V_t \rightarrow 2\pi r \times \delta \times L(n-1) = 3\alpha\Delta T\pi r^2 L \tag{11}$$

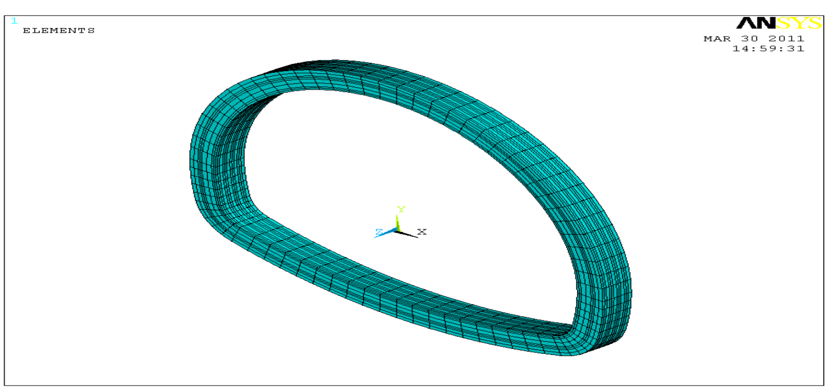
then :

$$\Delta T = \frac{\eta(n-1)}{3\alpha} \tag{12}$$

where,
n : Corrosion volume expansion rate.



(a) Tunnel lining model



(b) Computation model

Fig. 1: Tunnel lining model

FINITE ELEMENT ANALYSIS

Finite Element (FE) analyses method is used to predict the contributions of corrosion damage for tunnel lining. The corrosion model components analyzed in isolation (i.e., concrete cover, bar diameter and lining thickness). This enabled to identify of the contribution for corrosion damage constituents to tunnel lining performance deterioration.

Model description: The ANSYS software is used to analysis the corrosion in tunnel lining. The tunnel lining model is shown in Fig. 1. The model structure is consisted the 3D solid element and SOLID 65 for reinforced concrete. The model has eight nodes and three degrees of freedom for each node, while the translations in the nodal is in x, y and z directions. The model element is capable of plastic deformation, crushing and cracking in three orthogonal directions for each integration point. The solid element simulated concrete cracking with a smeared cracking approach. Moreover, the model structure is consisted with a 3D truss element and LINK8 for discrete steel reinforcement that consisted of two nodes and three degrees of freedom at each node, while translations in the nodal is in x, y and z directions. The reinforcing steel is modeled by using nonlinear truss elements rigidly (SOLID 45) that connected to the surrounding concrete elements by representing a perfect bond between concrete and reinforcing steel. For corrosion models, truss elements are not rigidly that connected to the surrounding concrete elements. The analyses are performed by using a quasi-displacement control technique that incorporated with high-stiffness springs at the loading point locations to accelerate solution times without loss of precision.

The model construction may divide into liner elasticity and non-linear elasticity which use concrete structure design standard (GB50010-2002).

The load parameter for non-linear stage is shown as follows:

$$\sigma = f_c[1-(1-\varepsilon/\varepsilon_o)^2]..when..0\le\varepsilon\le\varepsilon_o \qquad (13)$$

$$\sigma = f_c..when...\varepsilon_0 \le \varepsilon \le \varepsilon_u \qquad (14)$$

where,

ε_0 : The strain, (0.002)

ε_u : The ultimate pressure strain, (0.0033)

f_c : design compressive strength

The William-Warnke theory is applied to estimate failure criterion through concrete tensile strength and bearing capacity definition.

The construction model selected the ideal elastic-plastic model that did not consider the corrosion rate, which is oversized, so the yield strength for corrosion steel bar calculates as below:

$$f_{ys} = \frac{1-1.077\rho}{1-\rho} f_y \qquad (15)$$

where, f_{ys} and f_y yield strength respectively before and after corrosion for steel bar (Mpa)

ρ : Steel bar corrosion section loss factor (%)

In the ANSYS, concretes material may behavior as brittle material. So the concrete failure criterion expression is as follows:

$$\frac{F}{f_c} - S \ge 0 \qquad (16)$$

where,

S : Is the expiration of surface, for principal stress

f_c : Single axle tensile strength

The corrosion crack will appear when the stress condition in the Eq. (16) is achieved.

Materials: The Zhuhai tunnel in the china takes as case study in this research. The material used for the model is shown as follows:

- **Concrete (C30):** The main material characteristics for concrete is the specific weight (γd) = 20 kn/m3, Density = 2500 kg/m3, Elasticity (Ed) = 2 Gpa, Elasticity (Ec) = 30 Gpa, Poisson's ratio = 0.21, Angle friction = 27°, Cohesive force = 0.2 Mpa, compressive strength (fcd) = 20.1 Mpa and tensile strength (fctd) = 2.01 Mpa
- **Steel (HRB335):** The main characteristics for steel are: poisson's ratio = 0.27, tensile strength = 300Mpa and density = 3000 Kg/m^3
- **Computation model:** The computation model parameter adopts the physical parameter of Zhuhai Tunnel Design notes. The model size is 4.5 time of holes in the longitudinal direction. Figure 1a shows the computation model design.

Computation parameter: The main idea of model is computation the corrosion in concrete and steel for tunnel lining. The main parameter of model is presented in the Table 1.

Table 1: The main computation parameter

Rank	lining thickness (cm)	Concrete cover mm)	Steel bar diameter (mm)
V1	45	50	22
V2	45	30	22

FINITE ELEMENT ANALYSIS RESULTS

- The corrosion cracks appear at the corner of a tunnel lining then in invert and vault because the

Fig. 2: Tunnel lining before the corrosion

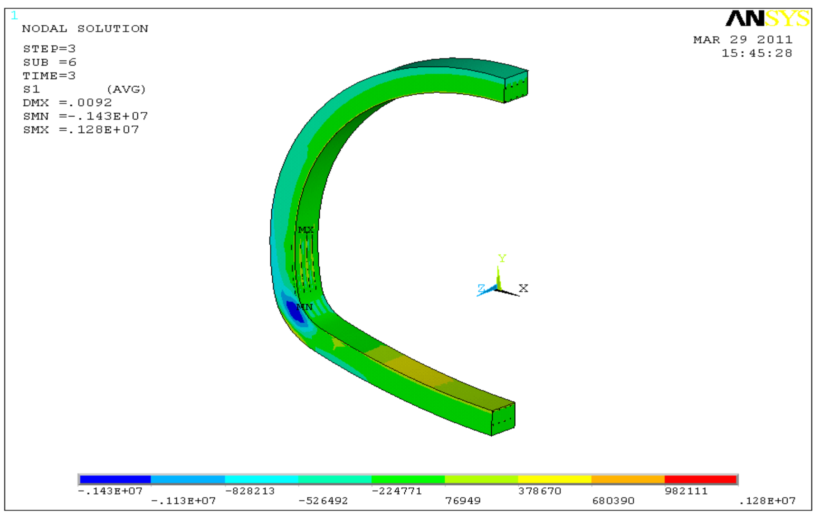


Fig. 3: Tunnel lining with corrosion rate 1.89%

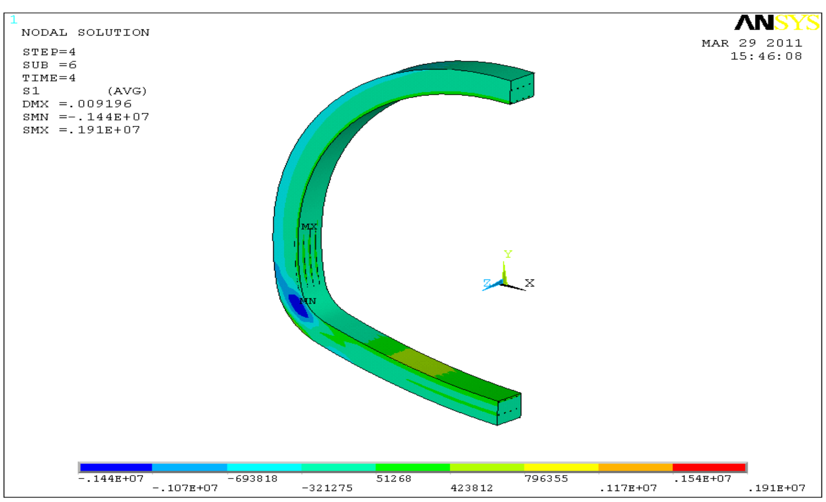


Fig. 4: Tunnel lining with corrosion rate 1.93%

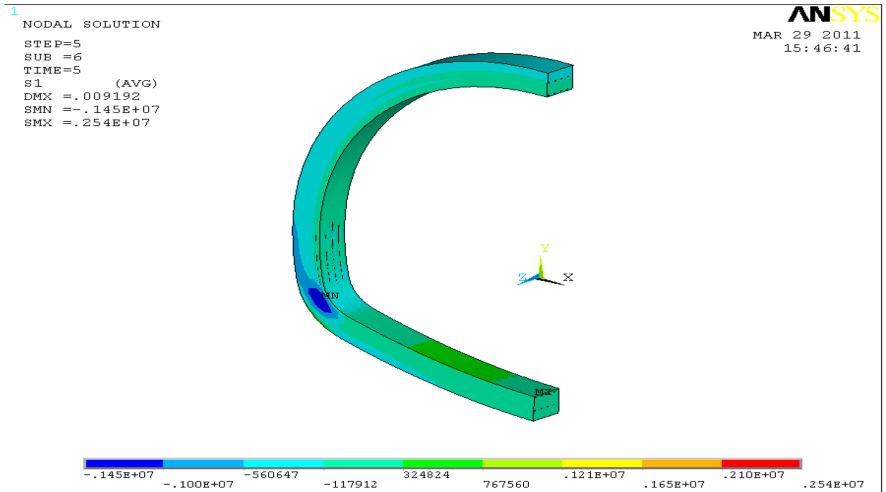


Fig. 5: Tunnel lining with corrosion rate 1.95%

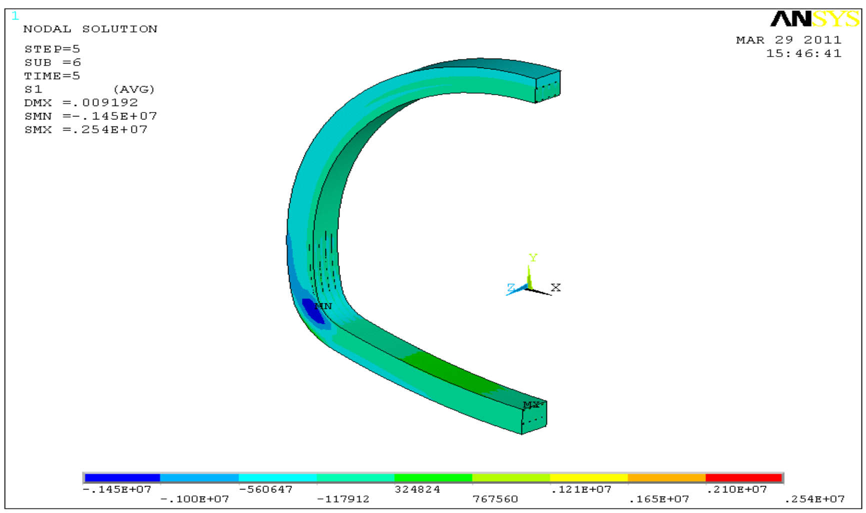


Fig. 6: Tunnel lining with corrosion rate 2.0%

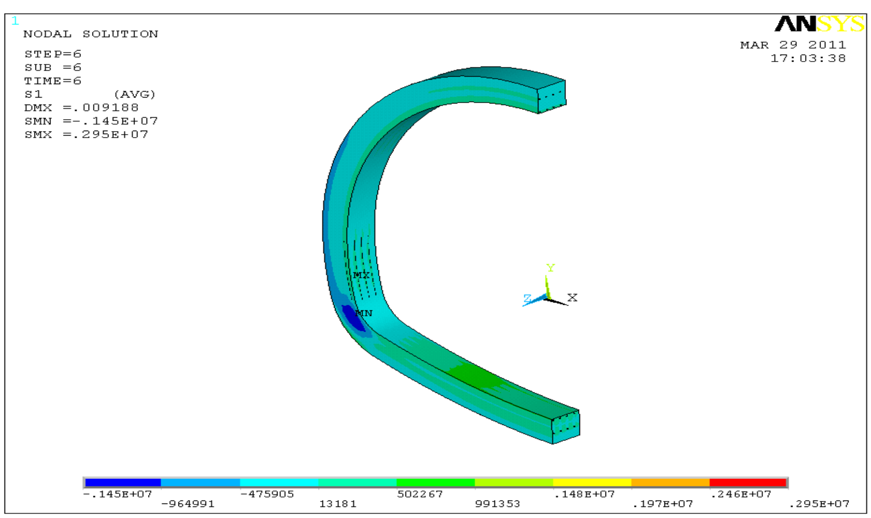


Fig. 7: Tunnel lining with corrosion rate 2.01%

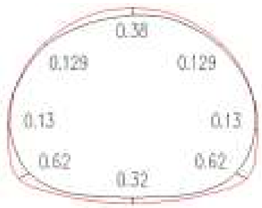


Fig. 8: Tunnel stress (mpa) with corrosion rate 0%

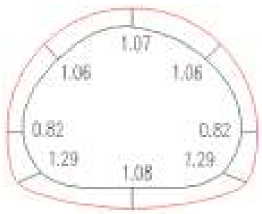


Fig. 9: Tunnel stress (mpa) with corrosion rate 1.89%

Fig. 10: Tunnel stress (mpa) with corrosion rate 1.93%

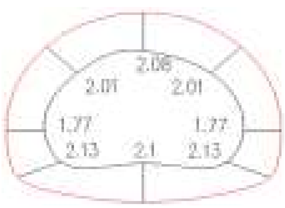


Fig. 11: Tunnel stress (mpa) with corrosion rate1.96%

Fig. 12: Tunnel stress (mpa) with corrosion rate 2.0%

Fig. 13: Tunnel stress (mpa) with corrosion rate 2.03%

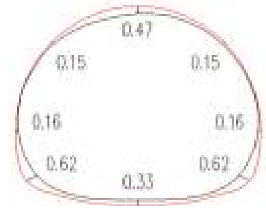


Fig. 14: Tunnel stress (mpa) with corrosion rate 0%

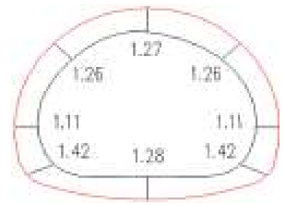


Fig. 15: Tunnel stress (mpa) with corrosion rate 1.89%

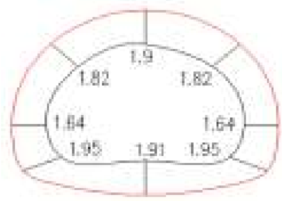


Fig. 16: Tunnel stress (mpa) with corrosion rate 1.93%

Fig. 17: Tunnel stress (mpa) with corrosion rate 1.96%

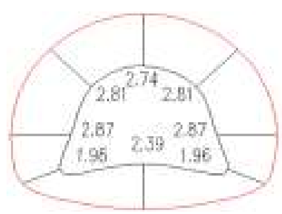


Fig. 18: Tunnel stress (mpa) with corrosion rate 2.0%

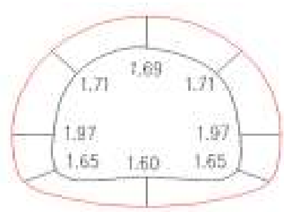


Fig. 19: Tunnel stress (mpa) with corrosion rate 2.03%

- maximum expensive stress will be in the corner then in invert and vault as shown in the Fig. 2 to 7.
- Variation computation parameter effect on tunnel lining
- **Operating mode 1:** Two lining thickness 45 cm, concrete cover 50 mm, concretes tensile strength 2.01 MPa and steel bar diameter 22 mm.

Figure 8 to 13 showed the stress behavior around tunnel lining when the corrosion rate changing from 0 to 2.03% with constant tunnel lining thickness, concrete cover and steel bar diameter.

- **Operating mode 2:** Two lining thickness 45 cm, concrete cover 30 mm, concretes tensile strength 2.01 MPa, steel bar diameter 22 mm.

The Fig. 14 to 19 shows the distribution stress around tunnel lining with different corrosion rate range 0 to 2.03%. The results show the concrete cover has positive effect on the increasing crack with corrosion rate increase. The two operating mode show the corrosion cracks appear at the corner of a tunnel lining then in invert and vault because the load distribution around tunnel lining. The relationship between the principle stress and corrosion for tunnel lining is defined as linear at fix time for analytical process.

CONCLUSION

In this study, after a critical review of relevant literature on numerical modeling of steel corrosion, a unified simulation model that is capable of performing tunnel lining corrosion modeling by using a FEM through applying temperature expansion to steel during the process of numerical simulation.

Because the steel bar corrosion, the lining of the tunnel has certain force under the adjacent load, along the steel bar corrosion, when the main tension in the concrete lining had change, the corrosion rate has been bigger, if the tension is biggest. The stress distribution is not uniform around the tunnel lining, therefore the crack location in tunnel lining also not uniform. The corrosion cracks appear at the corner of a tunnel then in invert and vault because the maximum expensive stress will be in the corner then in invert and vault. The internal force in the concrete lining changes differently when the corrosion rate change. Moreover, the thickness of concrete cover and the tunnel lining thickness have a positive impact on the expansive stress for reinforcement concrete during propagation of the corrosion process.

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