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Deformation and crack analysis of tunnel structure subjected to static distributed load using Pseudoshell model

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Abstract. The objective of this research is to study the deformation and crack in shotcrete of tunnel structure subjected to distributed static load. Tunnel is modeled as two dimensional finite element model using commercial finite element software, namely ATENA (*Advance Tool for Engineering Non Linear Analysis*) version V5. Non linear material models for concrete and reinforcing bars are adopted. For deformation and crack analysis, pseudoshell model is adopted in which fictitious crack opening is assumed occur first in pseudoshell then propagate to the tunnel structures. Three variations of pseudoshell thickness of 30 mm, 60 mm and 100 mm are used. The development of crack opening and propagation of crack and its displacement due to the increasing of static load is therefore analyzed. The analytical results show that the dummy load and displacement at the crack opening width of 1 mm for the pseudoshell thickness of 30 mm, 60 mm and 100 mm are 48 kN/m and 48,33 mm; 55 kN/m and 42,75 mm; 67 kN/m and 35,5 mm respectively. The relationships between dummy load, displacement and crack opening width are closely linear.

1. Introduction

With the increasing of infrastructures development such as tunnel to support transportation network, it is important to analyze the deformation and crack of structures during their serfice life. Crack will markedly reduce the durability of concrete segment, and finally influence the entire durability of tunnel [1]. Therefore, study on crack form, distribution and origin will be helpfull to strengthen the weak part of segment, and effectively improve the service life of tunnel.

Most research focus on stress and displacement of tunnel structures but not crack problem[2][3]. Some of researcher studied the crack formation of tunnel structures during construction period such as the reasons of cracks in segment in process of manufacture and erection process [4] and the using of hybrid method to research the crack behavior of shotcrete tunnel during 50 days after construction [5]. During service life, tunnel structures are subjected to static load due to soil pressure and traffict load such as movement of trains. There is a lack of research on the deformation and crack formation of tunnel structures during their service life. Therefore, in this research, the deformation and crack formation and propagation of tunnel structures during their service life subjected to static distributed load using pseudoshell model by two dimensional finite element method is studied.

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With the understanding of deformation and crack of tunnel strauctures during their serfice life, we can predict how long the serfice life of the structures and when the structures start to have crack. Therefore, the repairing and strengthening of the structures can be performed at the right time to extend the service life of the structures and to prevent the failure of the structures.

2. Literature Review

2.1 Shotcrete tunnel structure and material model

If high flexibility is required during tunnel excavation (e.g. in difficult ground condition and/or in urban areas), the New Australian Tunneling Method (NATM) has proved to be a powerfull mode of construction. In NATM method of tunnelling, shotcrete is used as a mainly material in tunnel. Shotcrete lining is a coating applied to the freshly dug tunnel cross section which has a thin layer and has a flexible shell. In general, shotcrete layer consists of two layers of reinforcement in the form of a grid. As known from reinforced concrete design, the present of reinforcement leads to a distribution of cracks finally resulting in a stabilized crack pattern. Cracking of shotcrete is caused by bending moments in the shell induced by heterogeneous soil and rock conditions. Moreover, shrinkage and thermal gradients (both in space and time) result is tensile loading favoring the development of cracks [5].

Hybrid methods combining the in situ measurements of displacements by means of monitoring system with a constitutive law for shotcrete were developed [6]. They allow the quantification of stress states in shotcrete shells. The employed material model for shotcrete has to account the chemical, thermal and mechanical cross effects [7]. Later, the proposed material model was extended towards considerations of creep and towards modelling of brittle failure [8,9].

The structural model proposed by Lackner and Mang [5] was aiming at real-time applications of the hybrid method on site. It is characterized by several simplifications concerning the deformation and stress state of the shotcrete shell as follows:

1) The change of the longitudinal curvature of a shell section is negligible.
2) A smooth displacement field is assumed. As long as the tunnel shell does not collapse (which would result in a localization of displacement), this is reasonable assumption.
3) Perfect bond is assumed between the shotcrete shell and the surrounding rock.
4) During the deformation, the thickness of the shell is assumed to be constant. Because of the small thickness of the shell, this assumtion is reasonable.
5) Lines which are perpendicular to the interior surface of the tunnel shell right after installation, remain perpendicular to the interior surface during the deformation. Because of the small thickness of the shell, this assumtion is reasonable.
6) Only axial stresses in the circumferential and longitudinal directions are considered. Since shotcrete shell are loaded predominantly by biaxial stress states stemming from circumferential and longitudinal deformations, this assumtion is reasonable.

An axial strain in circumferential direction is determined by approximating the displacement field locally by means of a linear finite beam elements. The axial strain in the longitudinal direction is determined by means of interpollation between the measured displacement components in the longitudinal direction [5].

The thermochemomechanical material model for shotcrete developed by Lackner and Mang [5] is formulated within the framework of thermodynamics of chemically reactive porous media. It is based on a macroscopic description of phenomena on the microlevel of the material by means of state variables. In the material model, two external varibles (strain tensor and absolute temperature) and six internal varibles (degree of hidration, tensor of plastic strains, vector of hardening variables, viscous strains, macroscopic flow strains and viscous slip) are used [7,8].

The ductile behavior of shotcrete subjected to a multi-axial state of compressive stresses is accounted for by hardening Drucker-Prager model. This material model is suitable for the simulation of predominantly biaxial stress state. Microcracking of shotcrete is modeled by means of the maximum tensile stress (Rankine) criterion. According to assumption 6) above, two Rankine criteria are employed to control the tensile stress of shotcrete in the circumferential and longitudinal directions. The use of two hardening forces allows consideration of cracking in the circumferential and longitudinal directions as two independent processes. Hence, in contras to isotropic softening, the strength in one direction remains unchanged when the crack in the other direction is opening.

As stated above, the present of reinforcement leads to a distribution of cracks finally resulting in a stabilized crack pattern. The formation of a stabilized crack pattern is accounted for by the average crack spacing. The interaction between the reinforcement bars and the surrounding shotcrete, the so-called tension-stiffening effect, results in an increase of a stiffness and strength of the composite material. The tension stiffening effect is considered within the material model for shotcrete by increasing the fracture energy by the factor γ, with $\gamma > 1$. Both the crack spacing and the factor γ depend on the material properties of shotcrete and steel, the geometric properties such as the shotcrete cover, the effective tension height for shotcrete and the reinforcement ratio [5].

2.2 Pseudoshell model

In analyzing the structural behaviors and assesing the structural safety of aging tunnel such as railway tunnels, roadway tunnels, and waterway tunnels of hydraulic power facilities, available analytical approaches can be classified primarily into two categories. One is to model the time dependent behavior of the surrounding geological materials with a simplified frame model for tunnel lining [10-12], in which hinges are introduced into the frame to model cracking in the lining concrete. The other is to model the lining with simplified boundary conditions, mostly with spring supports [13]. In the latter approach, the smeared crack method is often used to model the non linear material behavior due to the occurrance of cracks in the lining. As is often observed during tunnel inspections, aging tunnels are often plagued with various kind of cracking problem, where the crack-mouth-opening displacements (CMODs) of the two longitudinal cracks that were located respectively at the spring line and in the arch area rearched several milimeters. In most the cases, due to the lack of data measured on the cross-sectional deformation, these crack patterns and CMODs serve as important indices for evaluating the safety of these underground structures [14].

Shi [14] proposed a pseudoshell model which is based on the beam theory that ensured the uniqueness of the solution on deformation when the beam subjected to the same ratio of load to flexural regidity for analyzing the crack on tunnel lining. By stiffening the lining in the pseudoshel model to increase its flexural rigidity, theoretically it is still possible to obtain the true lining deformation under certain conditions. To achieve this, crack analysis is indispensable. By applying relevant loads to the pseudoshell with the aim of reproducing the observed cracking behavior, craking analysis is carried out based on the extended fictitious crack model (EFCM). When the tip a crack reaches the peseudoshell, a plastic hinge is introduced into the shell, allowing a rigid body rotation to take place at the crack surfaces while the crack analysis is continued using a crack-opening displacements (COD) controlled algorithm. Hence, the cross-sectional deformation of the tunnel can be obtained at any specified CMODs. Next, a quasi loosening zone model is used to calculate the ground pressure. Based on the assumption that the ground deformation must equal to the cross-sectional deformation of the tunnel, the external load can be obtained by ajusting the extent of the loosening zone through iterative computation. To fasilitate crack analysis in pseudoshell model, the EFCM employs two modeling techniques. Before a crack penetrates the lining, crack analysis is carried out by the crack-tip-controlled modeling method. As soon as the tip of a crack reaches the pseudoshell, a COD-controlled algorithm is required for the crack analysis.

3. Numerical Method

3.1 Numerical model

The numerical model used in this study is Sieberg tunnel, Austria. The tunnel has 10.42 m wide and 8 m high as shown in Figure 1. The tunnel constructed by shotcrete having the thickness of 330 mm. The shotcrete is reinforced by steel wiremesh. The diameter of wiremesh is 6 mm and spaced at 100 mm. The thickness of shotcrete cover is 30 mm. The compressive strength, Young modulus and Poisson’ratio of concrete are 39.6 MPa, 40.8 GPa and 0.2, respectively. The tensile strength, Young modulus and Poisson' ratio of wiremesh are 440 MPa, 200 GPa and 0.3, respectively.

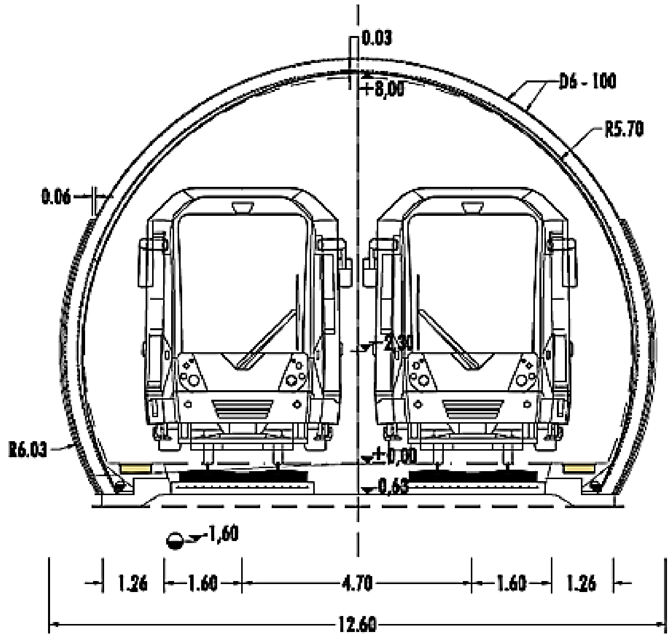

Figure1. Cross section of Sieberg tunnel, Austria

The tunnel is modeled as two dimensional (2D) finite elemen (FE) model using commersial finite element software, namely ATENA (Advance Tool foe Engineering Non Linear Analysis) version V5 [15]. A 5.8 m long distributed load is applied on the left side of the tunnel using pseudoshel model as shown in Figure 2. Three variations of pseudoshell thickness of 30 mm, 60 mm and 100 mm are analyzed. The steel material for pseudoshel is adopted.

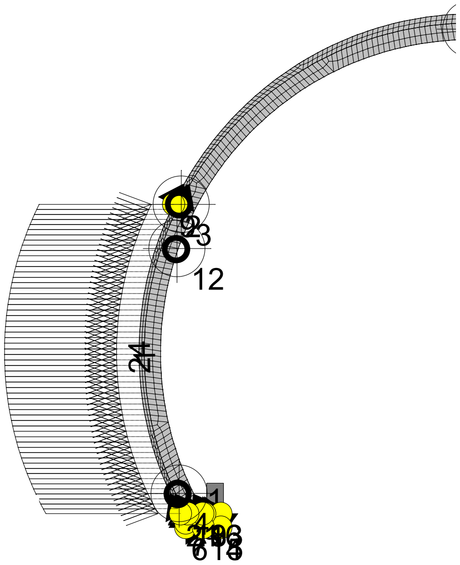

Figure 2. 2D FE model of tunnel with 5.8 m long distributed load on the left side (only half part of FE model is shown in the figure)

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3.2 Constitutive models

Concrete is modeled as a plane stress element as shown in Figure 3. Stress-strain models shown in Figures 4 and 5 are adopted for concrete and steel materials, respectively [15,16,17]. For pseudoshell, an elastic isotropic plane stress element is used. A smeared crack with fix crack model (Figure 6) is adopted in the analysis. For cracking modeling, the Rankine fracture criterion is adopted. The criterion is as follows:

$$F_i^f = \sigma_{ii}^t - f_{ii}^t \leq 0 \tag{3.1}$$

where: F_i^f = Rankine fracture criterion, σ_{ii}^t = elastic parameter, and f_{ii}^t = concrete tensile strength.

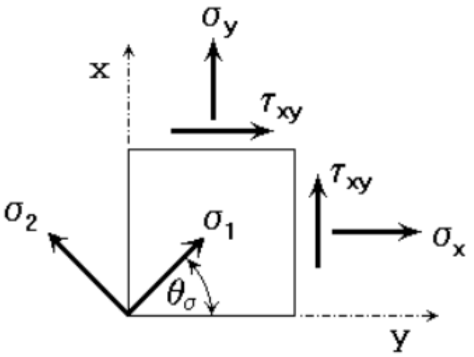

Figure 3. Plane stess element for concrete

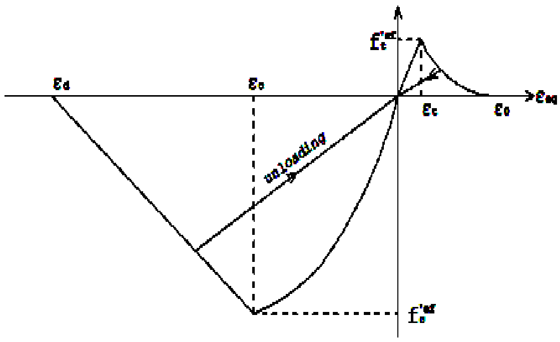

Figure 4. Stress-strain model for concrete

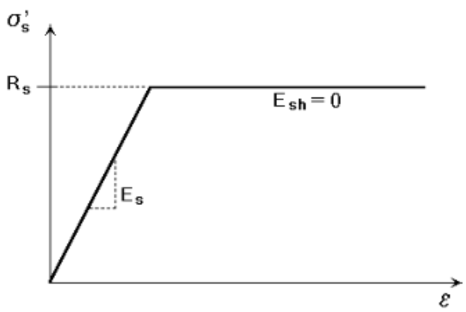

Figure 5. Stress-strain model for steel

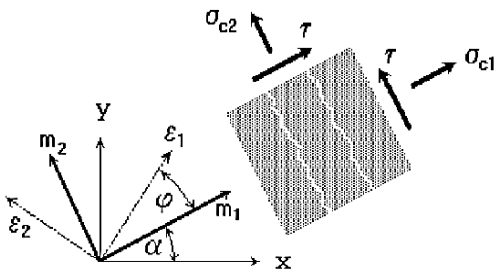

Figure 6. Fix crack model

3.3 Analytical procedure

The analysis is conducted by loading controll using ATENA software [15]. The loading increment for each step is 0.1 kN/m. The modified Newton-Raphson method is used as the confergence algorithm. The fictitious crack opening is assumed occur first in pseudoshell then propagate to the tunnel structures. The maximum crack mouth opening displacement (CMOD) of 1 mm is set. The displacements and crack are monitored at 100 monitoring points.

4. Numerical Results

From 100 monitoring points in this study, the maximum displacements for all variations of pseudoshell thickness occur at the monitoring point 9 as shown in Figure 7. Figure 8 shows the relationship between displacement and CMOD of tunnel structure at monitoring point 9. From this figure, it can be seen that the relationship is almost linear. The thicker the pseudoshell thikcness is the lower the displacement is. The displacements at the crack opening width of 1 mm for all variations of pseudoshell thickness are shown in Table 1.

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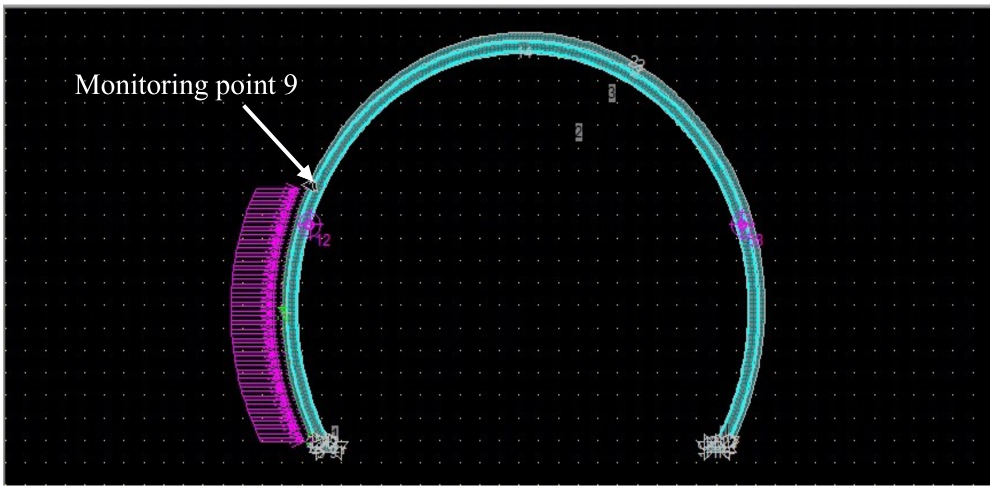

Figure 7. Monitoring point 9

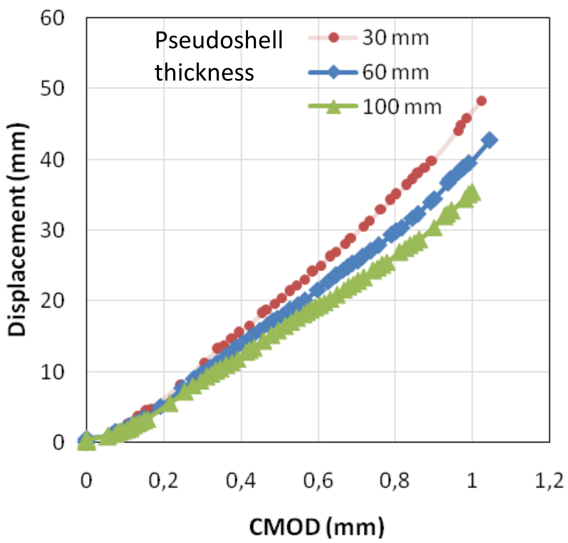

Figure 8. Displacement and CMOD relationship at monitoring point 9

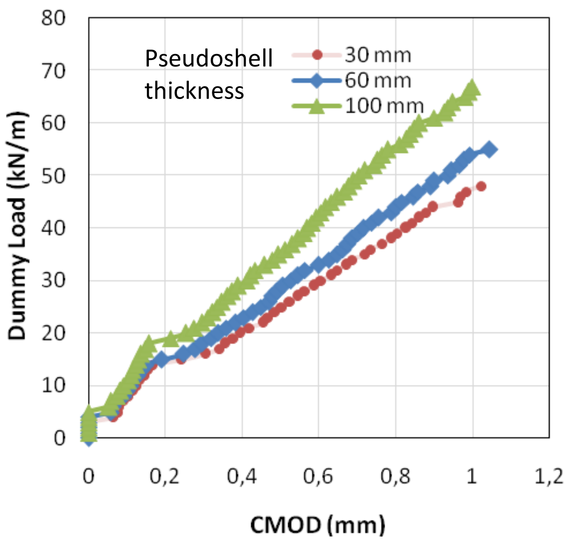

Figure 9. Dummy load and CMOD relationship at monitoring point 9

Figure 9 shows the relationship between dummy load and CMOD of tunnel structure at monitoring point 9. From this figure, it can be seen that the relationship is almost linear. The thicker the pseudoshell thikcness is the higher the load is. The displacement at the crack opening width of 1 mm for all variation of pseudoshell thickness is shown in Table 1.

Table 1. The displacements and dummy loads at the crack opening width of 1 mm

Pseudoshell thickness (mm)	Displacements at crack opening width of 1 mm (mm)	Dummy loads at crack opening width of 1 mm (kN/m)
30	48,33	48
60	42,75	55
100	35,5	67

Figures 10 and 11 are the displacement and dummy load at the crack width of 1 mm as a function of pseudoshell thickness. While the maximum displacement decreases linearly with increasing of pseudoshell thickness, the maximum dumly load increases.

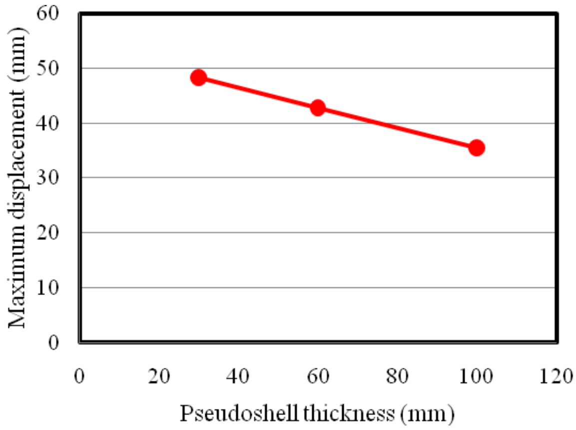

Figure 10. Displacement at the crack width of 1 mm and pseudoshell thickness relationship

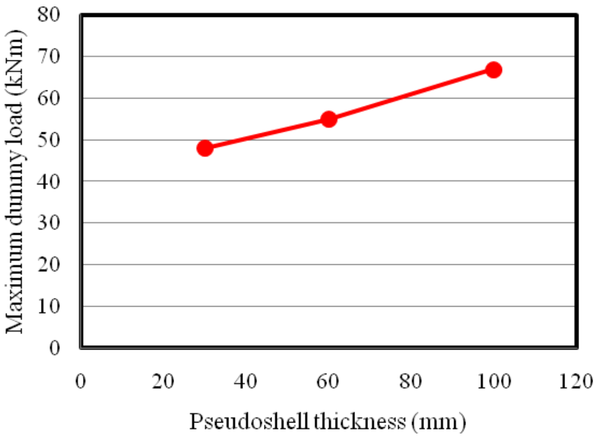

Figure 11. Dummy load at the crack width of 1 mm and pseudoshell thickness relationship

5. Conclusions

Analysis of deformation and crack of tunnel structure subjected to distributed static load was carried out. The following conclusions are drawn from this research.

1. The maximum displacements of the tunnel at the crack opening width of 1 mm for the pseudoshell thickness of 30 mm, 60 mm and 100 mm are 48,33 mm, 42,75 mm and 35,5 mm, respectively. The maximum displacement decreases with increasing of pseudoshell thickness.
2. The dummy loads of the tunnel at the crack opening width of 1 mm for the pseudoshell thickness of 30 mm, 60 mm and 100 mm are 48 kN/m, 55 kN/m and 67 kN/m, respectively. The dummy load increases with increasing of pseudoshell thickness.
3. The relationships between dummy load, displacement and crack mouth opening displacement are closely linear.

6. Acknowledgments

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