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Numerical simulation of the failure mechanism of circular tunnels in transversely isotropic rock masses

S. Y. Wang*

*Centre for Geotechnical and Materials Modelling
Civil, Surveying and Environmental Engineering
The University of Newcastle
Callaghan, NSW 2308, Australia
Email: Shanyong.Wang@newcastle.edu.au*

S. W. Sloan

*Centre for Geotechnical and Materials Modelling
Civil, Surveying and Environmental Engineering
The University of Newcastle
Callaghan, NSW 2308, Australia
Email: Scott.Sloan@newcastle.edu.au*

C. A. Tang

*School of Civil & Hydraulic Engineering
Dalian University of Technology, Dalian, P.R. China, 116024
Email: catang@mechsoft.cn*

W. C. Zhu

*Centre for Rock Instability and Seismicity Research
Northeastern University, Shenyang, P.R. China
Email: zhuwancheng@mail.neu.edu.cn*

* Corresponding author

Abstract

This paper studies the failure mechanism for a circular tunnel in transversely isotropic rock using the numerical code Realistic Failure Process Analysis (RFPA). In RFPA, an elastic damage model is used to describe the constitutive law of the meso-scale elements, and the maximum tensile strain criterion and the Mohr-Coulomb criterion are adopted as damage thresholds to determine the tensile and shear damage respectively. A series of numerical simulations of the failure process for a plane circular tunnel in rock are conducted. Based on the simulations, two major failure modes around circular tunnels in transversely isotropic rock are numerically reproduced. Whether failure is caused by sliding along the laminated layers depends on the orientation of the laminated layers, the confining pressure, and the strength ratio of the laminated layers to the intact rock. Numerical simulations of the failure modes are given for different ratios of discontinuity strength to intact rock strength, as well as different dimensionless ratios of discontinuity width. Finally, both the failure process of tunnels in up-roll foliated rock masses and down-roll foliated rock masses are investigated by RFPA.

Keywords: Numerical simulations; Heterogeneity; Failure mechanism of tunnel; Confining pressure; Transversely isotropic rock

1. Introduction

The presence of discontinuities makes the evaluation of the mechanical behaviour of tunnels in rock masses a challenging task. The configuration of the rock laminated layers affects the mechanical behaviour of the rock mass and thus the precise failure mode of the tunnel. As discussed by Tien et al.(2006), it is thus important to understand the failure of the rock itself in order to understand the failure mechanism around a tunnel which is subject to peripheral stresses (see Fig. 1). These authors employed an experimental scanning technique to successfully observe the failure process and failure modes of transversely isotropic rock. The observations of Tien et al. (2006) give very valuable insight into the general mode of collapse.

Although some continuum models and empirical formula can represent the overall behaviour of a rock mass with randomly distributed laminated layers (Morland, 1974; Hoek and Brown, 1980; Gerrard, 1982; Fossum, 1985; Chen, 1986; Chen, 1990), these may not be able to represent the effect of laminated layers on the failure modes around a tunnel in a highly laminated rock mass. However, numerical models such as the finite element method can be employed to simulate the effects of highly laminated rock masses. For example, Wang et al. (2009) adopted a finite element formulation to model the deformation and failure process of highly laminated rock mass around excavations with different geometries. However, their work was limited to the case of a laminated layer dip angle of 45°. The stability of a tunnel in laminated rock depends strongly on the presence, orientation, spacing, and strength of the laminated layers in rock mass as well as the in situ stress field.

In order to identify the failure mode and strength of a rock mass affected by the orientation, spacing, and strength of laminated layers, a number of physical models have been reported (McLamore and Gray, 1967; Brown, 1970; Brown and Trollope, 1970; Brown and Hudson, 1972; Reik and Zacas, 1978; Yoshinaka and Yamabe, 1986; Niandou et al., 1997). These laboratory studies have provided a great deal of insight and many valuable results. However, the interaction between the laminated layers generally was negligible due to the difficulties in determining the stress re-distribution between the

laminated layers during the failure process of specimen. Bray (1966) applied Jaeger's single-weak-plane theory (Jaeger, 1960) to predict that the strength of a rock mass with multiple laminated layers was controlled by the laminated layer with the lowest strength. His theory is also based on the assumption that there is no interaction between laminated layers during the failure process. However, Amadei (1988) has argued that superposition of the effect of laminated layers on rock mass strength is not mechanically correct unless the interaction between laminated layers is considered. Therefore, the interaction of laminated layers due to the stress distribution must be considered when studying the failure mechanism of a tunnel in a laminated rock mass.

In general, potential instability of a tunnel in a laminated can be detected by examining (1) the tangential stress around the tunnel boundary, (2) the deformation of the tunnel boundary, (3) the area of plasticity around the tunnel, (4) the extent of any tensile stress states, and (5) opening of and/or slip in any discontinuities (Read et al., 1988). To simulate the beginning and development of the fracture processes in a rock mass realistically, an effective constitutive model should be capable of describing the complete stress-strain behaviour of the rock, both in the elastic as well as in the pre- and post-failure phases (Zhu et al., 2009). To predict the maximum load that a tunnel can support, finite element limit analysis can sometimes be used (Assadi and Sloan, 1991).

In the current study, RFPA (Realistic Failure Process Analysis), a well-recognised numerical code, is used to simulate the progressive fracturing of rock around a circular tunnel. This code has been used extensively to study progressive rock fracture (Tang, 1997; Tang and Kaiser, 1998; Zhu and Tang, 2004; Wang et al., 2006; Wang et al., 2010), and one of its unique features is that no a priori assumptions need to be made about where and how fractures and failure will occur. Indeed, cracking can occur spontaneously and may exhibit a variety of mechanisms when certain local stress conditions are exceeded. In this study, a series of uniaxial and biaxial numerical tests are conducted to investigate the mechanical behaviour of a circular tunnel in a laminated rock mass, with particular attention being paid to the failure process, the failure mode and the interaction of the laminated layers due to the stress redistribution during failure. The peak stress of

the complete stress-strain response of the rock tunnel model is used as an indicator of instability, and the effect of confining pressure on the failure mode is numerically simulated. The failure modes for different ratios of discontinuity strength to rock strength are also studied, as well as the failure modes for different dimensionless ratios of the width of laminated layer. Finally, the failure processes for a circular tunnel in both up-roll foliated rock masses and down-roll foliated rock masses are simulated by RFPA.

2. Overview of RFPA and model setup

Briefly, the RFPA^{2D} code (Tang, 1997) is a two-dimensional finite element code that can simulate the fracture and failure process of rock. To model the failure, the rock medium is assumed to be composed of many mesoscopic elements, whose properties follow the Weibull distribution (Weibull, 1939).

$$f(u) = \frac{m}{u_0} \left(\frac{u}{u_0} \right) \exp \left(- \left(\frac{u}{u_0} \right)^m \right), \quad (1)$$

where u is a mechanical parameter of the elements (Young's modulus or strength) and the parameter m defines the shape of the distribution function. The influence of the homogeneity index (m) of the rock on the failure modes has been investigated in previous publications (Tang, 1997; Zhu and Tang, 2004). In the current study, the homogeneity index for the laminated layer and intact rock is taken as 3 and 2, respectively (Wang et al., 2009). The effect of the homogeneity index of the laminated layers on the failure modes of tunnel is not considered.

In RFPA^{2D}, the finite element method is employed to obtain the stress fields in the mesoscopic elements. Elastic damage mechanics is used to describe the constitutive law of the meso-scale elements, and the maximum tensile strain criterion and the Mohr-Coulomb criterion are adopted as damage thresholds (Zhu and Tang, 2004; Zhu et al., 2005; Wang et al., 2010). According to elastic damage mechanics, the elastic modulus of damaged material is expressed as follows:

$$E = (1 - \omega)E_0, \quad (2)$$

where ω represents the damage variable, and E and E_0 are the elastic moduli of the

damaged and the undamaged material, respectively. When the mesoscopic element is in a uniaxial tensile stress state, damage occurs when the maximum tensile strain criterion is exceeded. The constitutive relation of the mesoscopic element can be expressed as (Zhu and Tang, 2004):

$$\omega = \begin{cases} 0, & \varepsilon > \varepsilon_{t0}, \\ 1 - \frac{\lambda \varepsilon_{t0}}{\varepsilon}, & \varepsilon_{tu} < \varepsilon < \varepsilon_{t0}, \\ 1, & \varepsilon \leq \varepsilon_{tu} \end{cases} \quad (3)$$

where f_{tr} is the residual tensile strength, λ is the residual tensile strength coefficient, which is given as $f_{tr} = \lambda f_{t0}$ with f_{t0} being the unconfined tensile strength. The parameter ε_{t0} is the strain at the elastic limit, called the threshold strain, and ε_{tu} is the ultimate tensile strain of the element which indicates complete damage of the element. The ultimate tensile strain is defined as $\varepsilon_{tu} = \eta \varepsilon_{t0}$, where η is termed the ultimate strain coefficient (Zhu and Tang, 2004; Zhu et al., 2005).

For multiaxial stress states, the element is subject to damage in the tensile mode when the equivalent major tensile strain $\bar{\varepsilon}$ exceeds the threshold strain ε_{t0} . The equivalent principal strain $\bar{\varepsilon}$ is defined by (Zhu and Tang, 2004; Zhu et al., 2005)

$$\bar{\varepsilon} = -\sqrt{\langle -\varepsilon_1 \rangle^2 + \langle -\varepsilon_2 \rangle^2 + \langle -\varepsilon_3 \rangle^2}, \quad (4)$$

where $\varepsilon_1, \varepsilon_2$ and ε_3 are three principal strains and $\langle \rangle$ is a function defined as follows (Zhu et al., 2005; Wang et al., 2010):

$$\langle x \rangle = \begin{cases} x, & x \geq 0, \\ 0, & x < 0. \end{cases} \quad (5)$$

For an element subject to a multiaxial state of stress, the constitutive law is obtained by substituting the equivalent strain $\bar{\varepsilon}$, defined by Eqs.4 and 5, for the strain ε in Eq.3. The damage variable is expressed as (Zhu et al., 2005; Wang et al., 2010):

$$\omega = \begin{cases} 0, & \bar{\varepsilon} < \varepsilon_{t0}, \\ 1 - \frac{\lambda \varepsilon_{t0}}{\varepsilon}, & \varepsilon_{t0} \leq \bar{\varepsilon} \leq \varepsilon_{tu}, \\ 1, & \bar{\varepsilon} > \varepsilon_{tu} \end{cases} \quad (6)$$

To account for the damage to an element when it is under compressive normal stress and shear stress, the Mohr-Coulomb criterion is adopted to define a second damage threshold according to (Wang et al., 2010):

$$\sigma_1 - \frac{1 + \sin \varphi}{1 - \sin \varphi} \sigma_3 \geq f_{c0}, \quad (7)$$

where σ_1 and σ_3 are the major and minor principal stresses, respectively, f_{c0} is the uniaxial compressive strength, and φ is the internal friction angle of the mesoscopic element. The damage variable ω is expressed as (Zhu et al., 2005; Wang et al., 2010):

$$\omega = \begin{cases} 0, & \varepsilon < \varepsilon_{c0}, \\ 1 - \frac{\lambda \varepsilon_{c0}}{\varepsilon}, & \varepsilon \geq \varepsilon_{c0}, \end{cases} \quad (8)$$

where f_{cr} is the residual uniaxial compressive strength, λ is also the residual strength coefficient, and $f_{cr} / f_{c0} = \lambda$ is assumed to apply when the element is under uniaxial compression.

If an element is under a multiaxial stress state, the maximum principal (compressive) strain ε_{c0} can be calculated at the peak value of the maximum principal (compressive) stress (Zhu et al., 2005; Wang et al., 2010):

$$\varepsilon_{c0} = \frac{1}{E_0} \left[f_{c0} + \frac{1 + \sin \varphi}{1 - \sin \varphi} \sigma_3 - \mu(\sigma_1 + \sigma_3) \right]. \quad (9)$$

where μ is the Poisson's ratio. It is assumed that the shear damage evolution is related only to the maximum compressive principal strain ε_1 . So the maximum compressive principal strain ε_1 of the damaged element is substituted for the uniaxial compressive strain ε_0 in Eq.8, to extend the formulation to handle shear damage under triaxial stress states (Zhu et al., 2005; Wang et al., 2010):

$$\omega = \begin{cases} 0, & \varepsilon_1 < \varepsilon_{c0}, \\ 1 - \frac{\lambda \varepsilon_{c0}}{\varepsilon_1}, & \varepsilon_1 \geq \varepsilon_{c0}, \end{cases} \quad (10)$$

In addition, in RFPA2D, failed elements (where all Gauss points have failed) are assumed to be the source of an acoustic event since they must release elastic energy stored during the deformation. Tang has derived the following important relationship between the damage parameter D and the AE (Acoustic Emission) counts N (Tang, 1997; Tang and Hudson, 2002):

$$D = \frac{N}{N_m} \quad (11)$$

where N_m is the accumulated AE count. By recording the number of damaged elements and associated amount of energy release, RFPA2D is capable of simulating the AE activities including their event rate, their magnitude and their location for underground excavations (Wang et al., 2009).

A number of validation studies using laboratory tests on rock and concrete have been conducted to test the above model for the fracture evolution and rock failure (Tang, 1997; Wang et al., 2006; Wang et al., 2010). In addition, the RFPA code was evaluated against laboratory tests and was successfully used to study the effects of heterogeneity and anisotropy on excavations (Wang et al., 2009).

2.3 Model setup

The *in situ* stress is described in terms of the vertical stress and horizontal stress, with the former given by

$$\sigma_v = \rho g H \quad (12)$$

where ρ is the density of the intact rock (kg/m^3), g is the gravity acceleration (m/s^2), and H is the depth (cover) below the ground surface (m). The horizontal stress is defined as

$$\sigma_h = K_0 \sigma_v \quad (13)$$

where K_0 is the coefficient of earth pressure. The aim of this study is to investigate the behaviour of a circular tunnel (with diameter D) in rock where $H \gg D$, so that the

stress conditions around the tunnel can be simulated approximately as shown in Fig. 2. Note that both σ_h and σ_v are applied incrementally until the specified in-situ stresses are attained.

In the following simulations, circular tunnels are considered with laminated layers at different dip angles. The laminated layers themselves are assumed to obey the Mohr-Coulomb criterion (i.e., elasto-perfectly plastic laminated layers), and the properties of the intact rock and the filling materials in laminated layers are listed in Table 1 (Tien et al., 2006). To simplify the analysis, the effects of the excavation process, rock support and reinforcement are not considered. The geometry and boundary conditions are shown in Figure 2. In order to simulate the complete stress-strain curve response, the vertical load is applied using displacement control. All the models are composed of 240×240 elements with common dimensions of $240 \text{ mm} \times 240 \text{ mm}$. The tunnel diameter is 60 mm. Table 2 describes the parameters used to study the influence of the dip angle and lateral compressive pressures, while Tables 3 and 4 describe the parameters for the study of the effects of the discontinuity width and rock strength, respectively. The case for the influence of the case for the up-roll and down-roll laminated layers is listed in Table 5.

The loads were applied by incrementally raising the vertical and horizontal loads simultaneously to the desired level of constant confining stress, and then increasing the vertical load (under displacement control) until the model collapsed. At each step, elements may undergo damage due to excessive tension or yielding from the Mohr-Coulomb criterion. The stress and deformation distribution throughout the sample is then adjusted instantaneously after each element rupture to reach the equilibrium state. At points which undergo increased load due to a redistribution of the stresses, further ruptures may be caused. The process is repeated until no further failures in the elements occur. More external displacement is then applied, with energy being stored in the elements during the loading process. This energy is released as acoustic emissions during the onset of element failures (Tang, 1998).

3. Numerically simulations and discussion

3.1 Failure process and modes for uniaxial compressive test

3.1.1 Tensile failure across laminated layers

Fig.3 shows the stress-strain plot of a transversely isotropic specimen with a low dip angle ($\alpha = 0^\circ$) under uniaxial compression. In the early stages of compression (point a), with an axial strain of 49% of the peak load strain ε_p , some microcracks and acoustic emission events (caused by element failures) occur in the laminated layers around the tunnel due to their lower strength and Young's modulus (Fig.4a). When the loading increases to 62% of ε_p (point b in Fig. 3), more microcracks develop in the laminated layers as shown in Fig. 4. It is observed that these microcracks start to propagate vertically downwards and cross intact rock layers, as shown in Figure 4b. This can be explained by the fact that, due to the existence of the tunnel, the joint material exerts tensile strain on the intact rock layers, and with the increase of tensile strain, tensile cracks occur in the latter when the maximum tensile strain criterion (Equation 3) is satisfied. This mechanism is similar to the experimental results observed in Tien et al. (2006).

At a strain of 80% of ε_p (point c in Fig. 3), the microcracks start to propagate upwards, as shown in Fig. 4c. At a strain of 98.5% of ε_p (point d in Fig. 3), the stress level approaches the peak strength (σ_p) and new cracks start to propagate horizontally towards the left of the tunnel. These cracks are mainly in the laminated layers. In the meantime, the vertical cracks continue to interconnect with one other, parallel to the direction of the axial load and across different layers (Fig. 4d). At a strain of 120% of ε_p (point e in Fig. 3), new cracks start to propagate horizontally towards the right of the tunnel. During this stage, more new cracks cross the intact rock material. Together with new cracks in the laminated layers, the whole cracked area expands as the strain level increases. It is noted that even in the final failure stage ($\varepsilon = 1.3\varepsilon_p$, point f in Fig. 3) new cracks are also observed in both the intact rock and the laminated layers. In the end, macro-cracks in the right of the tunnel develop and start to propagate in the vertical direction parallel to the direction of axial load, as shown in Fig. 4f.

Fig. 5 shows the predicted final modes of failure during uniaxial compression of the tunnel in a foliated rock mass with varying dip angles ($\alpha = 0^\circ, 15^\circ, 30^\circ$). For the zero -dip specimen under axial compression ($\alpha = 0^\circ$), tensile cracking dominates the failure process. However, as the dip angle increases ($\alpha = 15^\circ, 30^\circ$), more shear cracking occurs in conjunction with tensile cracking. Fig. 6 shows the corresponding stress-strain curves and the corresponding AE events in the material surrounding the tunnel. It can be seen that the peak strength of the specimen decreases gradually when the dip angle increases from $0^\circ, 15^\circ$ to 30° . Similarly, the strain at the peak stress decreases when the dip angle increases from $0^\circ, 15^\circ$ to 30° . This indicates that, even for the low-dip specimens, the failure modes and the stability of the specimen are also influenced by laminated layers in the rock.

3.1.2 Shear failure along laminated layers

Fig. 7 shows the stress-strain plot of transversely isotropic specimen with a low dip ($\alpha = 45^\circ$) under uniaxial compressive loading, while Fig. 8 shows the corresponding failure process. When the strain reaches 31% of the peak load strain ε_p (a stress level at 43% of σ_p , point *a* in Fig. 7), micro-cracks start to occur and cluster in the direction of the left diagonal. Afterwards, the micro-cracks propagate in this direction (Fig. 8b). Not until the strain reaches 62% of the peak strain (point *c* in Fig. 7) do the micro-cracks start to propagate in the right diagonal direction. Figure 7d shows the propagation of micro-cracks in the direction of both the left and right diagonals. When the peak strength is reached (at a strain level of 0.41%, for point *e* in Fig. 7), additional micro-cracks interact and cluster in the diagonal direction. During this process, all the cracks occur in the laminated layers with none crossing the intact rock layers. When the stress level reaches 98% of the peak value σ_p (point *f* in Fig. 7), a sudden shear failure occurs along the discontinuity, as shown in Fig. 8f.

It is worth noting that for the case of ($\alpha = 45^\circ$), the shear cracks along the laminated layers dominate the failure process of the specimen. Indeed, the strength of the specimen

is mainly controlled by the strength of the filling material in laminated layers. Fig. 9 shows the final failure modes for the medium-dip ($\alpha = 45^\circ, 60^\circ, 75^\circ$) specimens after uniaxial compression. From these results, it appears that the failure of the medium-dip specimens is mainly caused by the shear stress around the tunnel reaching the Mohr-Coulomb criterion of Equation 7. Fig.10 shows the stress-strain curves and the corresponding AE events surrounding the tunnel. Here the strain at the peak stress decreases as the dip angle increases from 45° to 60° to 75° . However, the peak stress decreases as the dip angle increases from 45° to 60° , but then increases as the dip angle increases from 60° to 75° .

3.1.3 Tensile-split along *laminated* layers

Fig. 11 shows the stress-strain relationship of a transversely isotropic specimen with a dip angle of $\alpha = 90^\circ$ under uniaxial compression. Fig. 12 shows the corresponding numerical failure process. Under loading, the intact rock and the material of laminated layer have the same axial deformation but, since the stiffness of former is higher than that of the latter, the intact rock layers are more highly stressed. As the strength of the laminated layers is lower than that of the intact rock, this is where the tensile cracks first occur. At 16% of the peak strain ε_p (corresponding to 17% of the peak stress level σ_p , point *a* in Fig. 11), micro-cracks start to occur and cluster in the laminated layers around the tunnel (Fig. 12a). When the strain reaches 61% of the peak strain (point *b* in Fig. 11), more cracks cluster in the two laminated layers closest to the tunnel and cause failure within these layers. Subsequently, micro-cracks propagate and cause failure in the other laminated layers when the strain reaches 79% of the peak strain (point *c* in Fig. 11).

When the peak strength is reached (point *d* in Fig. 11), many of the laminated layers lose their strength due to the development of extensive tensile cracking. This explains the phenomenon of delamination (macro-splitting) that occurs along the discontinuities that are parallel to the applied load (Tien et al., 2006). In addition, some cracks occur in the layers of intact rock, resulting in these layers losing their ability to sustain load. When the stress drops to 82% of the peak stress σ_p under further loading (point *e* in Fig. 11), a sudden failure occurs due to more tensile cracks forming along the discontinuities, as

shown in Figs. 12e. Finally, when the stress drops to 41% of the peak value (point *f* in Fig. 11), many more cracks occur in the rock material layers which result in the failure of the whole specimen (Fig. 12 f).

In summary, due to the anisotropy of rock, the collapse of a tunnel is a complex failure process characterised by the initiation, propagation and coalescence of many cracks around the tunnel. Three main failure modes were presented above. In addition, as the stress-strain curve can express the overall stability of the tunnel, Fig. 13 shows a numerical simulation of the relationship between the dip direction angle, peak strength and the associated strain. From this Figure it can be seen that both the peak strength and the strain at the peak stress decrease gradually as the dip angle decreases from 0° to 60°. However, both of these quantities increase as the dip angle increases from 75° to 90°.

3.2 Influence of lateral confining pressure on the stability of tunnel in transversely isotropic rock masses

In this section, total 28 numerical simulations with various dip angles ($\alpha = 0^\circ, 15^\circ, 30^\circ, 45^\circ, 60^\circ, 75^\circ$, and 90°) and confining pressures of 0, 4, 12 and 30 MPa are carried out (see Table 2). They aim here is to study the influence of the lateral confining pressure on the stability of tunnels in transversely isotropic rock. Fig. 14 shows a comparison of the failure modes for different lateral confining pressures (0 and 4MPa) and different dip direction angles. As the confining pressure provides a lateral constraint, it prevents the development of tensile cracks. Accordingly, shear fractures tend to initiate and develop along a major shear plane. For the example with a lateral confining pressure of 4MPa, an obvious shear band occurs for specimens with low dip angles of 0°, 15° and 30°. These shear bands follow the classical pattern along the diagonal of the square samples. For the specimens with moderate dip angles of 45°, 60° and 75°, the shear bands are more prominent than those developed in the unconfined case, with the shear fractures mostly occurring in the laminated layers. For the specimen with a vertical dip angle of 90°, tensile cracks occur in the laminated layers despite the lateral constraint provided by the confining pressure. Shear fractures also develop to form a shear band that crosses both laminated layer and rock mass layers.

Fig. 15 shows selected stress-strain curves for different lateral confining pressures (0 and 4MPa) and different dip direction angles (0° and 30°). As expected, the stress-strain curves for the cases with a lateral confining pressure of 4 MPa lie above those for the cases with a lateral confining pressure of zero. Indeed, the peak stress levels for the former are 70MPa and 60MPa, respectively, for dip angles of 0° and 30° while the corresponding cases for the zero confining pressure are 50MPa and 40MPa.

This aspect is investigated further in Fig. 16, which compares the predicted peak strength versus confining pressure for various samples with different dip angles. All the peak strengths increase linearly with lateral confining pressure but, not surprisingly, the influence of the lateral confining pressure is dependent on the dip angle.

Based on the numerical results, the peak strength of the specimen is controlled by both the properties (stiffness and strength) of the filling materials in laminated layers and the intact rock. For the case of the low-dip specimen (e.g. $\alpha=0^\circ$), the peak strength is mainly controlled by the properties of intact rock. However, with the increase of dip angle, the influence of the properties of the intact rock weakens, while the effect of the filling materials of laminated layers strengthens, until the dip angle reaches 60° . However, as the dip angle continuously increases from 60° to 90° , the laminated layers with lower stiffness and strength gradually lose their ability to support load due to the effects of tensile cracking. For example, when the dip angle is 90° , the peak strength of the specimen is mainly controlled by the properties of intact rock. When the dip angle is 60° , the peak stress is mainly determined by the properties of the filling material in the laminated layers. Since both the stiffness and strength of the filling material in the laminated layers are much lower than those of intact rock, the peak stress reaches the lowest point when the dip angle is 60° . This is the reason that the peak strengths decreases when the dip angle increases from 0° to 60° , but then start to increase once the dip angle exceeds 60° in Fig. 17.

3.3 Influence of the properties of the filling materials in laminated layers on the stability of the tunnel under uniaxial compression

To investigate the influence of the properties of the filling materials in laminated layers on the stability of the tunnel, their compressive strength and indirect tensile strength, as well as their Young's modulus, are varied as a ratio to the corresponding strength of the intact rock. These ratios are taken as 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9 and 1, with a ratio of 1 corresponding to no laminated layers in the rock mass. The dip angle of the laminated layers was fixed at 45° (see Table 3).

Fig. 18 shows the predicted failure modes for specimens with various ratios of strength and Young's modulus of filling material in laminated layer to intact rock. For low ratios of 0.1 and 0.2, failure occurs by sliding along the laminated layers with very few cracks crossing the intact rock. In these cases, the strength of the specimens is controlled by the strengths of the laminated layers and the final fracture orientation is parallel to them. As the strength ratio is increased to 0.3 - 0.5, although the final failure mode is still caused by sliding along the laminated layers, some cracks cross the rock layers (Figs. 18c, d and e). In fact, for these cases, both the strength of laminated layers and the intact rock control the overall strength of the tunnel. For higher strength ratios of 0.6 - 0.8, more cracking occurs in the rock layers (Figs. f, f and h) and this material starts to dominate the overall load capacity of the tunnel. Finally, when the ratio of strength reaches 0.9, the failure mode does not follow the direction of the laminated layers but, instead, occurs in a vertical direction under tension. In these cases, the strength of the tunnel is governed primarily by the strength of the intact rock.

Fig. 19 shows the peak strengths of the tunnels as a function of the ratio of the strength of filling material in laminated layer to intact rock strength. This Figure indicates that the peak strength increases linearly with the strength ratio. Fig. 20 illustrates the strain at the peak strength as a function of the ratio of the Young's modulus of filling material in laminated layer to intact rock Young's modulus. From this Figure, it is clear that the strains at the peak strengths also increase with the ratio of Young's modulus. These

results indicate that not only the dip angle of the laminated layers, but also the strength and Youngs' modulus of the filling material in them, have a significant influence on the failure mode and overall stability.

3.4 Influence of the spacing of laminated layer on the stability of the tunnel under uniaxial compression

This section investigates the influence of the spacing of laminated layer on the tunnel stability. This is done by varying the ratio (a/b), where a is the width of intact rock layers and b is the width of the laminated layers (see Figure 2). Width ratios of 1, 2, 4, 6 and 8 are studied for a constant dip angle of 45° (see Table 4).

Fig. 21 shows the predicted failure modes for the various laminated layer spacing ratios (a/b). All the failure modes stem from sliding along the laminated layers, regardless of the spacing of laminated layer. This indicates that the spacing of laminated layer does not affect the failure mode profoundly for cases where the dip angle and the property of the laminated layers are the same. This is because the cracks always occur in the weakest zone and propagate along this zone until the tunnel fails. Typically, one laminated layer contributes most to the overall failure, with its properties and dip angle controlling the failure mode.

Fig. 22 shows the variation of the peak strength predictions with spacing of laminated layer. As the peak strength ranged from 26MPa to 29MPa over the full range of spacing of laminated layer, this parameter has only a modest affect on the overall strength of the tunnel for the case considered.

3.5 Failure of tunnel in rock mass with up-roll and down-roll laminated rock mass under uniaxial compression

In this section, the influence of both up-roll and down-roll laminated layer on the failure mode of the tunnels is considered. The boundary conditions and the laminated layer

spacing ratios are listed in Table 5.

Fig. 23 illustrates the progressive failure process of a tunnel in an up-roll laminated rock mass. For a strain of 0.5%, cracks start to occur in the laminated layers below the tunnel. When the strain increases to 0.9%, some cracking in the rock mass occurs in the diagonal direction. Overall failure of the tunnel occurs once the strain reaches 1.6%, with extensive cracking in the diagonal direction. Fig. 24 shows the simulated stress-strain curve and the associated AE counts during uniaxial compression of the tunnel in an up-roll laminated rock mass. Two obvious stress drops occur during the failure process and a peak strength of around 45MPa is reached.

Fig. 25 shows the simulated failure process of a tunnel in a down-roll laminated rock mass, with Fig. 26 showed the corresponding stress-strain curve and the associated AE counts. Unlike in Fig. 23, cracking always occurs along the laminated layers during the failure process for down-roll laminated layer, and there is no failure zone formed in the direction of the diagonal. In addition, comparing Fig. 26 and Fig. 24, it is evident that the peak strength for down-roll laminated layer (30 MPa) is much lower than that for up-roll laminated layer (45 Mpa). This is because the up-roll laminated layer benefits from effects of arching, which allows the tunnel to support higher loads.

4. Conclusions

Using the Rock Failure Process Analysis code (RFPA2D), this paper has investigated the failure process and failure modes of a circular tunnel in transversely isotropic rock. Due to the influence of anisotropy, the failure process is complex and characterised by the initiation, propagation and coalescence of cracks around the tunnel. Some of the key results are summarised below:

- 1) The failure process of a tunnel in a transversely isotropic rock mass under uniaxial loading has been modelled ($\alpha = 0^\circ$). For low-dip specimens ($\alpha = 0^\circ, 15^\circ, 30^\circ$) under axial compression, tensile cracking dominates the failure process with the influence of shear cracking increasing gradually as the dip angles increases. Cracks can

develop along the laminated layers as well as parallel to the direction of the applied load. The peak strength of the tunnel decreases gradually as the dip angle increases from 0° to 30°.

- 2) For medium-dip formations ($\alpha = 45^\circ, 60^\circ, 75^\circ$), failure is mainly caused by shear stresses around tunnel which satisfy the Mohr-Coulomb criterion and lead to damage. The strain at the peak stress decreases with increases in the dip angle over this range. However, the peak stress decreases as the dip angle increases from 45° to 60°, but decreases thereafter.
- 3) For highly dipping formations ($\alpha = 90^\circ$), the laminated layers with lower stiffness and strength lose their ability to support load due to the effects of tensile cracking. This may explain the phenomenon of delamination (macro-splitting) which occurs along laminated layers in a direction which is parallel to that of the applied load (Tien et al., 2006).
- 4) As expected, the numerical results show that confining pressures provide a lateral constraint and suppress the development of tensile cracks. However, shear cracks can initiate and form a major shear plane. All the peak strengths decreased when the dip angle decreased from 0° to 60°, and start to increase beyond this range.
- 5) The numerical results show that the strength and modulus of the filling materials in laminated layers can affect the failure mode and final stability of tunnel significantly. As expected, when the stiffness and strength of the filling materials in laminated layers is close to that of the intact rock, the failure modes and overall strength of the tunnel are less affected by the presence of laminated layers.
- 6) For the cases considered, the laminated layer spacing did not affect the overall strength of the tunnel significantly. This is because the cracks in the rock mass first occurred in the weakest zones which are the laminated layers. Once these cracks are initiated, they propagated along the laminated layers until final failure occurred. Moreover, usually only one laminated layer in the direction of the diagonal contributed most to the final failure of the specimen.
- 7) The failure processes of tunnels in a rock mass with both up-roll layers and down-roll layers were simulated. The peak strength of the tunnels in the down-roll formation was much lower than that for the up-roll formation. This was because up-

roll formations benefit from the effects of arching, which permit the tunnel to carry higher loads.

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