Safety Analysis of the Secondary Lining Structure of Existing Tunnel with Cracks

Shuang Cai¹*, Hao Ding²

¹China Merchants Chongqing Communication Research & Design Institute Co., Ltd., Chongqing, 400067, China
²China Merchants Chongqing Communication Research & Design Institute Co., Ltd., Chongqing, 400067, China

*Corresponding author’s e-mail: caishuang@cmhk.com

Abstract. Because cracking of the secondary lining is one of the most common diseases in road tunnel, it is of great practical significance and theoretical value to analysis and research on the safety of lining structure of existing tunnel with cracks. Based on crack models of fracture mechanics, the calculation method of safety evaluation for the secondary lining structure of existing tunnel with cracks was discussed through numerical analysis. The bearing capacity of non-destructive lining and cracked lining was analyzed and compared by model tests. Results showed: (1) the finite element method of fracture mechanics could be used to evaluate the safety of the secondary lining structure of existing tunnel with cracks. (2) The size order of the required load when the cracks occurred in the different parts; The arch foot is smaller than the vault; the vault is smaller than the haunch; the haunch is smaller than the invert. (3) When the crack was located at the crown and arch foot, it had the most significant influence on the safety of lining structure. (4) The bearing capacity of the lining structure declined because of cracks, and it decreased by 37.5% when there was longitudinal crack at the bottom of the inverted arch of tunnel.

1. Introduction

Secondary lining cracking is one of the most common defects found in highway tunnels. This defect deteriorates over time to such extent that compromises safe operation of the tunnel. However, the causes of lining structure cracking are very complicated and its mechanism lacks in-depth research. Consequently, it is of great relevance and theoretical value to explore how to assess the safety of existing tunnels with cracks. Some researches were previously done by other researchers on lining cracking. For example, literature [1] proposed a calculation model of tunnel lining crack based on fracture mechanics theory and calculated the effect of crack depths and angles on tunnel lining stability using contact element; analysis was also performed of the entire process from lining cracking to failure in different loading modes based on the finite element nonlinear analysis theory for reinforced concrete [2]. However, these previous researches mostly focused on qualitative and cracking analyses using complex models with little attention to the safety aspect of lining structure with cracks, and cannot be easily understood by ordinary tunnel maintenance personnel. Moreover, they mainly used numerical calculation methods, lacking model tests on the bearing capacity of lining structure with cracks. In response, this paper presents further study on safety assessment method for linings with cracks and their bearing capacity model test so as to offer practical methods and knowledge of actual safety status of such linings.
2. Structural Safety Assessment Method for Lining Structure with Cracks

2.1. Cracks model

Prior to safety assessment calculation for lining structure with cracks, a crack model has to be selected. Currently there are 3 kinds of mainstream numerical analysis model for concrete cracks [3-6], as follows:

(1) Discrete cracks model

In the discrete crack model it is assumed that a crack appears on the boundary of each element. The crack grows when the nodal force at the node ahead of the crack tip exceeded a tensile strength criterion. Then, the node is split into two nodes and the tip of the crack is assumed to propagate to the next node to ensure the crack is always on element boundaries. This model can naturally describe the process of crack generation and propagation and calculate crack depth provided the location and orientation of the crack are known. During calculation constant adjustments to element boundaries are required, thus involving lots of computational effort.

(2) Distributed cracks model

Totally different from the previous model, the distributed crack model does not require direct simulation of cracks. It assumes concrete maintains continuity after cracking and allows application of various failure criteria and strength theories. It also assumes when tensile stress in an element exceeds the ultimate tensile strength of structural material, a crack will appear perpendicular to the tensile stress direction, losing tensile stiffness in normal direction, and is distributed uniformly in the element. This model does not require knowing the location and orientation of the crack beforehand or changing the grid and nodes since the crack is formed automatically. But it cannot be used to calculate crack width.

(3) Fracture mechanics model

The fracture mechanics model is intended mainly to study the propagation and instability of existing structure cracks and consider the effect of stress concentration at the tip of cracks on crack propagation. This model requires the location of crack be known beforehand and can simulate crack width, length and depth.

For tunnel linings with cracks which have already existed, the fracture mechanics model is selected for the purpose of this paper taking into account the characteristics of the above three models.

2.2. Assessment method

Given the discreteness of secondary lining concrete material and multiaxial strength, excessive pursuit of mathematical refinement cannot necessarily increase computational accuracy while making computation too complicated. On the other hand, it involves paying more price to obtain parameters, leading to more loss than gain. This paper provides safety assessment of lining structure with cracks using the fracture mechanics model and Griffith theory. The Griffith theory states that a crack will propagate when the effective stress is greater than or equal to the energy required for crack propagation. Using the elliptical hole stress solution in elastic mechanics Griffith derived the following strength criteria:

\[
\begin{align*}
\sigma_1 + 3\sigma_3 &< 0, \\
\sigma_1 + 3\sigma_3 &< 0, \\
\sigma_3 &+ 3\sigma_1 &< 0, \quad \sigma_i = (\sigma_i - \sigma_s)^2 \div (\sigma_i + \sigma_s)
\end{align*}
\]  

(1)

By comparing maximum tensile stress on the crack tip obtained by FEM with the ultimate tensile strength of lining structure material, it can be determined whether the crack propagates.

To determine whether a crack in tunnel lining structure will propagate the following equation is used:

\[ s_f = \frac{\sigma_i}{[\sigma]} \]  

(2)
where $s_f$ — cracking criterion; $[\sigma]$ — ultimate tensile strength of lining concrete material;

Thus if $s_f \leq 1$ the crack in the tunnel structure will not propagate; if $s_f > 1$ the crack in the tunnel structure will propagate.

2.3. Calculation example
Calculation on a lining structure with secondary lining thickness of 50cm and invert of a tunnel in Class V surrounding rock (Figure 1) is presented hereunder using ANSYS finite element software.

![Figure 1. Calculation example of lining structure section](image1.png)

![Figure 2. Calculation model of initial crack in arch](image2.png)

This model simulates tunnel concrete lining using the PLANE42 element (which is defined by four nodes with two degrees of freedom at each node: translations UX and UY in the (nodal) x and y-directions) and simulates constraints on the lining structure by surrounding rock using link10, a two-dimensional spar element. The modeling process is simplified significantly by imposing uniformly distributed load directly with surf153 (surface effect element) without the need for conversion to nodal load. To increase computational precision the load increment should be as small as possible. Considering computational efficiency load increments of 30KPa are selected. When cracking load is between two levels of load, the load increment shall be subdivided evenly to establish the cracking load. For a lining structure with cracks, the fracture mechanics model is used to simulate cracks, with initial cracks placed at the crown, hance, arch foot and invert bottom.

Numerical simulation analyses show: stresses in the lining structure under load concentrate at the crack; stress and strain increase with increasing load, and the crack will propagate. Maximum tensile stress in the lining structure with cracks under load is shown in Figure 3.
From Figure 3 it is known that:

1. Taking maximum tensile stress as safety criterion, when the load reaches 0.225MPa maximum tensile stress in intact lining is 2.061MPa. This value exceeds the ultimate tensile strength of concrete material of secondary lining structure, leading to cracking of the lining structure. The amount of load required to cause initial crack at different positions is as follows: arch foot < crown < hance < invert.

2. From curve trends shown above it is known that stress rises considerably with increasing load if initial crack is created at the crown and arch foot. If the crack is created at the invert, the stress rises by an approximately equal value Compared with intact lining. This suggests the crack at the invert has the least Impact on the safety of lining structure whereas the cracks at the crown and arch foot pose the highest level of hazard.

3. For lining with cracks, the stress will sharply increase if load continues to increase after maximum tensile stress exceeds the ultimate tensile strength of lining material.

3. Bearing Capacity Model Test for Lining with Cracks

To further study the mechanical property of existing lining structure with cracks, the bearing capacity model test is performed. The model test has a scale of 1:10. The secondary lining is made from a mixture of sand, cement and gypsum and reinforced with steel mesh. Measuring points are arranged at the crown, spandrel, hance, arch foot and invert respectively (Figure 4).
The test employs industrial grease (friction factor \( \tan \phi = 0.05 \); viscosity \( \eta = 400 \text{Pa} \cdot \text{s} \); bulk modulus 1.6GPa) to simulate surrounding rock. Forces acting on the lining structure surrounded by low friction rock material are illustrated in Figure 6.

![Figure 6. Low friction rock material \( \sigma_1 = \sigma_2 = \sigma_3 \)](https://example.com/figure6.png)

During the test, a jack applies 1:1 load in horizontal and vertical directions to simulate the original ground stress field at \( \sigma_x : \sigma_y = 1:1 \). The model box is filled with grease via which the load is transferred to secondary lining. By controlling the movement of the actuator, load is applied incrementally by 1.56KPa increments. At each increment the load is held for 3-5min. The next increment is applied only after the previous one and lining deformation have ceased. This procedure is repeated until the test specimen fails. During this process data are gathered several times.

This test includes analysis and comparison of the bearing capacity of intact lining and the lining structure with cracks at invert. Internal forces of the lining structure under load in the models are illustrated in Figure 7 to Figure 9.

![Figure 7. Curve of Axial force—load](https://example.com/figure7.png)

a) Curve of Axial force—load for intact lining  

b) Curve of Axial force—load for cracked lining

Figure 7. Curve of Axial force—load
From the above figures it is known that:

1) When the load reaches 12.48KPa the internal force of intact lining structure changes abruptly leading to structure failure; for a lining structure with longitudinal cracks at invert bottom, the internal force changes abruptly when the load reaches 7.80KPa leading to structure failure. The presence of cracks reduces the structure's bearing capacity by 37.5%.
(2) During load application on an intact lining structure, both maximum axial force and maximum bending moment occur at the hance. However, in terms of the direction of internal force, the axial force in this cross section is negative, i.e. compressive stress while the bending moment is always positive, resulting in tension on the inner side of the lining which is control cross section. The compressive stress from the axial force offsets part of the tensile stress from the bending moment, slowing down the growth of tensile stress in this cross section. In addition, the positive bending moment at the arch foot, where the compressive stress is lower, is second only to that at the hance. Therefore, these two places become control cross section of the tunnel while stresses in other cross sections are low.

(3) When longitudinal cracks are present at invert bottom, maximum bending moment occurs at the crown and invert bottom. The bending moment at the crown is negative, suggesting compression on the inner side of the lining. The axial force in this cross section is positive, with little tensile stress. This cross section is therefore under compression control, leading ultimately to crushing failure of the crown. In contrast, the bending moment at invert bottom is positive, with tension on the inner side of lining. The axial force in this cross section is negative, i.e. compressive stress, but small. Because the tensile strength of lining concrete material is much lower than its compressive strength, the crack propagates after the load continues to increase after crown cracking, leading ultimately to cracking failure of the structure.

4. Conclusions
To sum up:

(1) For tunnel linings with cracks it is a safety assessment method to model lining structure with cracks based on fracture mechanics FE theory, apply load incrementally for analyses and determine whether maximum tensile stress exceeds ultimate tensile strength.

(2) The calculation results show: The amount of load required to cause initial crack at different positions is as follows: arch foot < crown < hance < invert; stress rises considerably with increasing load if initial crack is created at the crown and arch foot, with the most significant influence on the safety of lining structure.

(3) The bearing capacity model test on lining structure with cracks shows: the presence of cracks reduces the structure's bearing capacity; the presence of longitudinal cracks at invert bottom reduces the bearing capacity of the lining by 37.5%.

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