Study on cracking behavior of tunnel linings with the diseases of void and lining insufficient thickness

Wei Han¹, Yujing Jiang¹*, Ningbo Li¹, Hengjie Luan², Xianlong Wu³

¹ Graduate School of Engineering, Nagasaki University, Nagasaki 852-8521, Japan
² College of Energy and Mining Engineering, Shandong University of Science and Technology, Qingdao 266590, China
³ Shandong Provincial Key Laboratory of Civil Engineering Disaster Prevention and Mitigation, Shandong University of Science and Technology, Qingdao 266590, China

Abstract. Typical tunnel diseases, such as lining cracking, void behind the lining, and lining insufficient thickness, can commonly occur in tunnel structure, seriously threatening the safety state of tunnel operation. In this research, to investigate the relationship between these diseases, the cracking behavior of tunnel structure with typical combined diseases of void behind the lining and lining insufficient thickness were concentrated on using the cohesive zone model (CZM) method. At first, the zero-thickness cohesive elements were inserted between the lining solid elements globally to determine the possible cracking zone, guaranteeing the randomness of cracking. Subsequently, the characteristics of crack propagation of linings with typical combined tunnel diseases were explored detailed under the applied gradual loading. Finally, to quantitatively explore the development of lining cracks, the statistics of cracks (including the number of damaged cohesive elements and crack area) were conducted. The main results of this study indicated that the distribution of void and lining insufficient thickness influences the cracking behavior obviously, and the cracking degree shows a positive relationship with the applied gradual loading. Furthermore, as the gradual loading increases, the number of damaged cohesive elements presents a significant increasing trend, and the number of damaged cohesive elements also shows a positive relationship with the void range. In addition, the crack area also shows a positive relationship with the applied gradual loading and the void range.

1. Introduction

Cracking of lining support structure is common in tunnels, which is prone to cause engineering disasters such as concrete spalling, and collapse, seriously threatening the safe operation of tunnel structure [1-5]. In addition, typical diseases such as void behind the lining and insufficient lining thickness can also appear in tunnel structures [6-7]. The existence of tunnel typical diseases will affect the cracking performance of linings to a certain extent [8]. Therefore, it is significant to make clear the cracking behavior of linings with typical tunnel diseases.

The main reasons, such as insufficient backfilling, water erosion, and gravity, will cause the void disease [9]. However, regarding the disease of lining insufficient thickness, the reason is mainly due to improper construction, resulting in insufficient excavation of surrounding rock [10]. Concerning the impact of these typical tunnel diseases, Zhang [11] investigated the effect of the void behind lining and insufficient lining thickness on the safety state of a double-arch tunnel structure, and the cracking
characteristics were explored with the Extend Finite Element Method (XFEM). Ding et al. [12] carried out the model tests to explore the mechanical and the fracture properties of reinforced concrete lining considering the symmetric and asymmetric voids, and the numerical simulation based on the concrete damage plastic model was subsequently established to study the damage behavior. Min et al. [13] paid attention to the mechanical behavior and the failure patterns of double-arch tunnels considering voids diseases. Che [14] studied the lining cracking characteristics based on the XFEM model, and the characteristic of crack propagation was explored. Zhang [15] studied the effect mechanism of lining defects of highway tunnel lining, and the concrete damage plastic model in Abaqus was applied to explore the cracking behaviors of concrete lining. Gong [10] evaluated the safety state of tunnel structure under the impact of the disease of insufficient lining thickness, and the XFEM in Abaqus was then applied to simulate the cracking behavior of the tunnel lining. Feng [16] conducted the laboratory test to explore the fracture characteristics of tunnel structure with void diseases, and the distribution of inner force was also investigated. Zhang [17] investigated the cracking behaviors of tunnel lining with void diseases, and the distribution of stress and the inner force were further studied. The cohesive zone model (CZM) was proposed by Dugdale [18] and Barenblatt [19], which recently has been widely applied to explore the damage behaviors of concrete structures [20-22]. Furthermore, the CZM method has also been extensively applied to describe the cracking behaviors of rock materials [23-25].

It can be observed that the mechanical and damage behaviors of tunnel linings have been widely investigated. Note that previous studies on cracking performance are mostly based on a single disease, such as void or lining insufficient thickness. However, information on the cracking behavior of tunnel linings with combined diseases of void and lining insufficient thickness is rather limited. In addition, the CZM method could describe the cracking behavior of the concrete structure. Unfortunately, fewer appeared in arched tunnel lining concrete structures with combined diseases, and its application should be further discussed. Therefore, the focus of this study is to explore the cracking behavior of tunnel structures with combined tunnel diseases based on the CZM method.

2. Model establishment

The numerical model established in this research can be demonstrated in Figure 1. The model dimension was arranged as a 3D model with the tunnel axial depth of 20m, in which the tunnel typical combined diseases of void and the lining insufficient thickness were considered. Concerning the void size, the range was set as 45°, and the length in the axial direction was set as 5m. Regarding the size of the lining insufficient thickness, the range was fixed as 45°. In addition, the distance between the void and the lining thickness was fixed as 1m. It should be indicated that since the void shape has little effect on the tunnel structure [26], the void thus can be set as a rectangular shape. Furthermore, it should be noted that the area with insufficient lining thickness is in contact with the rock mass. If the rock mass is not in contact with the lining in the local thickness insufficient zone, a local combined disease would be formed. To study the influence of local insufficient lining thickness separately, the rock mass and lining in the model are in contact in the model. Regarding the establishment of the numerical tunnel model, the cross-section of tunnel structure in this research was applied from the standard section of the highway tunnel [27]. Concerning the boundary conditions, the displacement of the surrounding rock on the left and right sides as well as the front and back directions were limited, and the vertical displacement at the bottom of the model was fixed. To be able to observe the cracking characteristics of the lining, a gradual vertical loading was applied to the top sides of the model. The boundary condition was also adopted by Wu [8] and Gong [10]. According to the Specification for Design of Highway Tunnels, the parameters of the corresponding materials can be displayed in Table 1, and the parameters of cohesive elements can also be obtained by Wu [8] as follows: initial tensile stiffness 17GPa/m, initial shear stiffness 7.35GPa/m, normal traction 6.5MPa, tangential traction 22MPa, I fracture energy 0.08N/mm, II fracture energy 0.185N/mm. In addition, it should be indicated that the cohesive elements should be set as zero thickness to ensure the original size of the model [23]. The solid elements and the inserted zero-thickness cohesive elements of the model can be presented in Figure 2.
Figure 1. Numerical model and the distribution of tunnel diseases.

(a) Insufficient thickness
(b) Void zone

Figure 2. Numerical elements: (a) solid elements; (b) inserted zero-thickness cohesive elements.

Table 1. Parameters of rock mass and tunnel lining materials.

| Parameters      | $\rho$ (kg/m$^3$) | $E$ (GPa) | $\nu$ | $c$ (kPa) | $\varphi$ ($^\circ$) |
|-----------------|-------------------|-----------|-------|-----------|---------------------|
| Rock mass       | 1800              | 1.5       | 0.35  | 150       | 20                  |
| Tunnel lining   | 2200              | 21        | 0.2   | /         | /                   |

3. Numerical results
3.1 Cracking behavior

In this section, the cracking characteristics of tunnel lining with combined diseases of void and lining insufficient thickness were explored and presented in Figure 3. Note that two typical perspectives were selected to observe the phenomenon of lining cracking. As can be observed from the perspective I in Figure 3, it can be found that on the outer surface of the lining, cracks mainly appear within the void zone. The main reason for this phenomenon is that the surrounding rock and the lining are not in contact within the void zone, resulting in the sharp reduction of the safety factors [28], which will be prone to cause the local failure of the lining. As the gradual loading increases, some cracks gradually appear at the area and the edge of the lining insufficient thickness zone. This cracking phenomenon can also be reflected by the test of Gong [10], which can further prove the rationality of the cracking results. It is worth noting that the cracking degree of the void zone is larger than that of the area within the insufficient lining thickness zone. This is because the surrounding rock and the lining are in...
contact within the insufficient lining thickness zone in this research, forming a relatively well contact state. With the increment of the applied vertical loading, the number of longitudinal cracks further increases. In addition, it is observed that significant longitudinal cracks mainly occur in the arch springing. Perspective II was also presented in Figure 3 to explore the fracture characteristics in the lining inner surface. It is observed that significant ring cracks occur at the edge of the void zone, and there are both longitudinal cracks and ring cracks generated at the void zone and the edge of the lining insufficient thickness zone. In addition, cross patterns of ring cracks and longitudinal cracks are prone to occur on the inner surface of the area between the lining insufficient thickness and the void zone. Overall, the cracking behaviors are significantly affected by the distribution of the void and lining insufficient thickness.

| Fracture behavior | Crack propagation | Crack further propagation | Crack further propagation |
|-------------------|--------------------|---------------------------|---------------------------|
| Perspective I     | Lining insufficient thickness | Void zone | Crack |
| Perspective II    |                     |              |                   |

**Figure 3.** Cracking behavior of tunnel linings with combined diseases of void and lining insufficient thickness.

### 3.2 Statistics of cracks

To make clear the evolution characteristics of cracks during the fracture process, the number of damaged cohesive elements and the area of cracks were investigated. It should be indicated that this section also focuses on exploring the effect of void range on the crack statistics of tunnel lining with the combined diseases, and the void range was set as 30°, 45°, 60°, and 90°, respectively. The corresponding statistics can be presented in Figure 4. It should be indicated that the 1MPa, 2MPa, 3MPa, 4MPa, 5MPa, 6MPa, and 7MPa during the gradual vertical loading process were selected as typical examples to explore the characteristics of crack statistics. The number of damaged cohesive elements can be presented in Figure 4a. It is noted that when the applied gradual load is less than 3MPa, the number of damaged cohesive elements is small. As the applied gradual load level further increases, the number of damaged cohesive elements changes significantly. Specifically, when the applied gradual load reaches to 5MPa-7MPa, the number of damaged cohesive elements is equal to 682, 4567, and 8614 for the void range of 45°, while for the void range of 60°, the numbers are 850, 5201, 9948, respectively. It can be observed that the number of damaged cohesive elements presents a positive relationship with the level of gradual load in the model. Concerning the effect of the void range on the number of damaged cohesive elements, note that the number is significantly affected by the void range. Specifically, when the applied gradual load level is reached to 5MPa, the number of damaged cohesive elements is 523, 682, 850, and 1382 for the void range of 30°, 45°, 60°, and 90°, while the number is equal to 3802, 4567, 5201, and 7148 when the applied load level is reached to 6MPa. Therefore, it is noted that the number of damaged cohesive elements exhibits a positive relationship with the increment of the void range in the model. Regarding the distribution of lining
crack area under the gradual vertical loading, the output results of statistics can be presented in Figure 4b. It is observed that the crack area can further increase with the increment of the applied loading. When the applied loading is larger than 5MPa, the crack area is increased sharply. In addition, it is also observed in this research that the crack area shows a positive relationship with the void range.

![Figure 4. Statistics of cracks in this model: (a) number of damaged cohesive elements; (b) crack area.](image)

4. Conclusions and Outlook

In this paper, the lining cracking behavior with the typical diseases of void and lining insufficient thickness was investigated. At first, the lining model was established with the CZM technique; Subsequently, the characteristics of cracking were explored; Then, the statistics of cracks (including the number of damaged cohesive elements and the crack area) were conducted. The main conclusions and the outlook in this research can be drawn as follows:

1. Cracking behavior is significantly affected by the distribution of void and lining insufficient thickness. The degree of cracking within the void zone of the outer surface of the lining is larger than that of the insufficient lining thickness zone. As the gradual loading increases, the degree of cracking will increase.

2. The characteristics of cracks are affected by the void range and the gradual load level. Specifically, in this research, the number of damaged cohesive elements and the crack area present a positive relationship with the void range and the applied gradual load.

3. In future work, it is significant to conduct the three-dimensional laboratory tunnel model test to further make clear the cracking behavior of tunnel linings with combined diseases of void and lining insufficient thickness. In addition, it is necessary to further optimize the numerical parameters in combination with the model test and further explore its cracking characteristics and failure mechanism deeply.

Acknowledgment

This research is funded by Shandong Provincial Natural Science Foundation (Grant No. ZR2019BEE065).

References:

[1] Wu XZ, Jiang YJ, Masaya K, Taniguchi T, Yamato T, 2017. Study on the Correlation of Vibration Properties and Crack Index in the Health Assessment of Tunnel Lining. *Shock Vib.* 2017, pp 5497457.

[2] Malmgren L, Nordlund E, Rolund S, 2005. Adhesion strength and shrinkage of shotcrete, *Tunn. Undergr. Space Technol.*, 20(1), pp 33–48.

[3] Xu GW, He C, Chen ZQ, Liu CK, Wang B, Zou YL, 2020. Mechanical behavior of secondary tunnel lining with longitudinal crack. *Eng. Fail. Anal.* 113, pp 104543.

[4] Wu XZ, Jiang YJ, Wang JH, Masaya K, Taniguchi T, Yamato T, 2017. A New Health Assessment Index of Tunnel Lining Based on the Digital Inspection of Surface Cracks. *Appl. Sci.* 7(5), pp 507.

[5] Zhang XP, Jiang YJ, Sugimoto S, 2018. Seismic damage assessment of mountain tunnel: A case study on the Tawarayama tunnel due to the 2016 Kumamoto Earthquake. *Tunn. Undergr. Sp. Tech.* 71, pp 138-148.
[6] Xue YD, Yang R, 2017. Effect of Void behind Mountain Tunnel Lining in Blasting Condition. 4th ISRM Young Scholars Symposium on Rock Mechanics, pp 10–13.

[7] Yu L, Bai SJ, Liu XX, Chen L, Bao LS, 2017. Study on the influence of tunnel lining thickness on bearing capacity of lining. Journal of Shenyang Jianzhu University (Natural Science), 33(6), pp 1039-1047.

[8] Wu XL, 2021. Study on the Influence of Voids behind Early Support of Highway Tunnel on Structure Safety and Crack Evolution, Shandong University of Science and Technology, Master thesis.

[9] Wang JF, Huang HW, Xie XY, Bobet A, 2014. Void-induced liner deformation and stress redistribution. Tunn. Undergr. Sp. Tech. 40, pp 263–276.

[10] Gong YP, 2019. Study on the tunnel structure safety under the impact of the lining thickness deficiency. Beijing Jiaotong University. Master thesis.

[11] Zhang X, 2018. A research on the impact of the voids behind lining and lining thickness deficiencies on the safety of a double-arch tunnel structure. Beijing Jiaotong University. PhD thesis.

[12] Ding ZD, Ji XF, Li XQ, Ren ZH, Zhang S, 2019. Influence of Symmetric and Asymmetric Voids on Mechanical Behaviors of Tunnel Linings: Model Tests and Numerical Simulations. Symmetry, 11(6), pp 802.

[13] Min B, Zhang X, Zhang CP, Gong YP, Yuan TF, 2018. Mechanical Behavior of Double-Arch Tunnels under the Effect of Voids on the Top of the Middle Wall. Symmetry 10(2), pp 703.

[14] Che ZJ, 2020. Study on the safety of the straight wall tunnel under the condition of void behind the lining. Qingdao University of Technology. Master thesis.

[15] Zhang S, 2020. Study on Influence Mechanism of Lining Defects and Bearing Capacity of Highway Tunnel Lining. Lanzhou University. PhD thesis.

[16] Feng G, 2013. A study on the Structure Security of Lining-Based on the influences of insufficient lining thickness and the voids existing at the back of lining. Beijing Jiaotong University. Master thesis.

[17] Zhang X, Zhang CP, Feng G, Han KH, 2017. Experimental studies on effect of voids behind tunnel linings on progressive failure process of tunnel structures. Chinese Journal of Geotechnical Engineering. 39(6), pp1137-1144.

[18] Dugdale DS, 1960. Yielding of steel sheets containing slits. J. Mech. Phys. Solids, 8(2), 100–104.

[19] Barenblatt GI, 1962. The Mathematical Theory of Equilibrium Cracks in Brittle Fracture. Adv. Appl. Mech. 7, pp 55–129.

[20] Song SH, Paulino GH, Buttlar WG, 2006. Simulation of Crack Propagation in Asphalt Concrete Using an Intrinsic Cohesive Zone Model. Journal of Engineering Mechanics 132 (11), pp 1215-1223.

[21] Zhang H, Zhang HW, Su F, 2015. The Introduction and Application of Cohesive Zone Model on Asphalt Concrete Fracture Behavior. Applied Mechanics and Materials 744, pp1320-1323.

[22] Wu ZJ, Zhang PL, Liu QS, Li WF, Jiang WZ, 2018. Dynamic Failure Analysis of Reinforced Concrete Slab Based on Cohesive Element Under Explosive Load, Engineering Mechanics. 35(8), pp 79-90.

[23] Zhang SB, Wang G, Jiang YJ, Wu XL, Li GX, He P, Yu, J.; Sun, L., 2020. Study on Shear Mechanism of Bolted Jointed Rocks: Experiments and CZM-Based FEM Simulations. Appl. Sci. 10, pp 62.

[24] Chang X, Guo TF, Zhang S, 2020. Cracking behaviours of layered specimen with an interface crack in Brazilian tests, Eng. Fract. Mech. 228, pp 106904.

[25] Huang D, Li B, Ma WZ, Cen DF, Song YX, 2020. Effects of bedding planes on fracture behavior of sandstone under semicircular bending test, Theor. Appl. Fract. Mec. 108, pp 102625.

[26] Liu HJ, 2007. Study on mechanical and numerical model for road tunnel defects diagnosis. Tongji University. PhD thesis.

[27] Ministry of Transport of PRC, 2004. Code for Design of Road Tunnel. China Communication Publisher Ltd., Beijing.

[28] Liu C, 2018. Study on mechanical characteristics of tunnel structure under the condition of void behind arch lining, Qingdao University of Technology, Master thesis.