STUDY ON THE REINFORCEMENT EFFECT OF PROTECTIVE SURFACE REINFORCEMENT FOR CRACKED LINING IN RAILWAY TUNNELS

Qizhu Jiao[1], Yalong Shi[2*], Congwen Yan[3], Peng Chen[4], Kai Liu[5]

Abstract

Designers often express concern about resource wastage caused by excessive reinforcement of lining cracks and the limited effectiveness of conventional repair methods such as plastering mortar and crack sealing, when subjected to construction defects and environmental degradation. To address these limitations and suppress further crack propagation, this study proposes a protective reinforcement method and evaluates its performance under surrounding rock pressure using finite element analysis. The results show that: (1) the first principal stress within the protective reinforcement remains well below the material's design strength, ensuring structural integrity; (2) no tensile damage occurs in the lining under either single-crack or mesh-crack conditions, confirming that the reinforcement effectively inhibits crack development; (3) reinforcement bars reduce stress concentration at crack tips, lower tensile stress, and improve the structural safety factor; and (4) retaining bars are unsuitable for reinforcing deep cracks (≥0.5H) due to their weak shear resistance and the complexity of deep crack formation. These findings provide a basis for optimising reinforcement strategies for cracked lining structures.

Received: *26 March, 2025*
Revised: *9 October, 2025*
Accepted: *26 November, 2025*

[1,3]China Railway Siyuan Survey and Design Institute Group Co., Ltd., Wuhan 430063.

[2,4,5]China Railway Southwest Research Institute Co., LTD, Chengdu, 611731.

****Corresponding author:***
shiyalong_crsi@163.com

DOI:
https://doi.org/10.54552/V86I4.288

Keywords:
Cracks, Protective covering steel, Railway tunnels, Reinforcement effect, Safety evaluation

List of Notations:

γ	is unit weight for material
μ	is Poisson ratio
E_0	is the elastic modulus of the material
H	is the lining thickness
SF	is the safety factor
f_t	is the design value of concrete tensile strength
K	is the minimum allowable safety factor
MPa	Mega pascal

1.0 INTRODUCTION

As the operational lifespan of tunnels increases, lining cracks have become one of the main issues affecting the safe operation of tunnels (Li *et al.,* 2018; Wang *et al.,* 2016; Li, 2020). In response to remediation measures for cracked linings, both domestic and international scholars have conducted a certain amount of research.

For example, Wang *et al.* (2010) calculated the lining safety factor under the action of longitudinal cracks in the Anji Tunnel. They proposed that for cracks in plain concrete segments where the safety factor meets the regulatory requirements, reinforcement should be done using mortar plastering. For cracks that do not meet the regulatory requirements, reinforcement should be carried out using I20a@550m+steel mesh + sprayed concrete.

Yu *et al.* (2017) used finite element software to study the reinforcement effect of combined components formed by steel plates and anchoring devices. The results showed that the combined structure could improve the stress characteristics of the cracks and the surrounding areas, prevent stress concentration, and restore the load-bearing capacity to a state similar to the intact lining.

Chen *et al.* (2014) classified the cracks in a certain railway tunnel into four levels (AA, A1, B, and C) based on the crack's length and width. They used finite element software to analyze the reinforcement effects of W steel strips + steel mesh + sprayed concrete and cross-joint anchor grout. The results showed that the W steel strip + steel mesh + sprayed concrete could increase the safety factor of the structure with longitudinal cracks from 0.92 to 2.69, while the cross-joint anchor grout could raise the safety factor from 0.97 to 2.51, meeting the regulatory requirements.

In addition to the aforementioned measures, common crack remediation techniques also include concrete lining replacement, corrugated sheet lining, partial replacement, and full replacement (Su *et al.,* 2020; Fu *et al.,* 2021; Yu *et al.,* 2021; Shao *et al.,* 2019; Wang *et al.,* 2017), all of which are now relatively well established. However, in reinforcement design, some designers have raised two concerns: first, whether excessive reinforcement or replacement measures for defective cracks in plain concrete linings may result in unnecessary resource expenditure; and second, whether cracks repaired only with surface plastering or grouting will continue to propagate if the grout quality is inadequate or if environmental factors alter the lining's stress state. In response to these concerns, this study adopts the approach of inhibiting crack initiation and propagation, using finite element software to evaluate the reinforcement performance of protective surface reinforcement. The aim is to provide guidance and support for similar remediation projects.

2.0 COMPUTATIONAL MODEL

2.1 Expansion and Prevention of Cracks

The core of tensile crack propagation is the change in material mechanical behaviour caused by stress concentration at the crack tip. The stress concentration at the tip of the crack leads to a sudden change in the mechanical properties of the material, which in turn promotes the continuous propagation of the crack. As shown in Figure 1, the crack tip includes three areas: Traction free macrocrack, Bridging zone, and Microcrack zone, among which the plastic damage characteristics of concrete materials need to be considered in the Bridging zone and Microcrack zone.

The stress-strain curve of materials considering concrete tensile damage is shown in Figure 2.

When the concrete material at the tip of the crack is in the post peak stage (D_t>0), the crack is in an unstable equilibrium state. Under the disturbance of the surrounding environment, the probability of crack propagation will greatly increase. Therefore, the core of suppressing the propagation of tensile cracks is to ensure that the stress at the crack tip is in a pre-peak state and has a certain safety margin, as show in

$$\begin{cases} D_t = 0 \\ SF = \dfrac{\sigma_1}{f_t} \geq K \end{cases} \tag{1}$$

Among them, K is the minimum allowable safety factor, and according to the *Railway Tunnel Design Code*, it is taken as 3.6.

2.2 Model Overview

Finite element software was used to study the stress characteristics of single-line tunnels (height 10.93m, width 10.67m, cross-sectional area 80.03m²) and double-line tunnels (height 10.98m, width 14.06m, cross-sectional area 118.80m^2) with single and mesh cracks. A "load-structure" model was used for calculations, with a lining longitudinal length of 12m and thickness of 45cm. The lining was simulated using solid elements, the foundation spring was simulated with spring elements, and the protective surface reinforcement was simulated using shell elements. Cracks were simulated using contact surfaces, assuming that no tensile or shear stresses are transmitted at the crack location, but compressive stresses are transmitted.

Given that cracks have a more significant impact on the stress of plain concrete linings, and past experience shows that cracks located at the crown have the most significant effect on the structural stress, calculations were carried out for a single longitudinal crack and mesh crack at the crown of an IV-grade surrounding rock plain concrete lining. According to the Railway Tunnel Design Code (TB10003-2016) (hereinafter referred to as "Tunnel Code"), the vertical load for a single-line tunnel with IV-grade surrounding rock is taken as 86.940kPa, and for a double-line tunnel, it is 112.153kPa. The lateral pressure coefficient is taken as 0.25. The secondary lining load-bearing ratio is taken as 50%. The models for the longitudinal crack and mesh crack at the crown are shown in Figures 3 and 4.

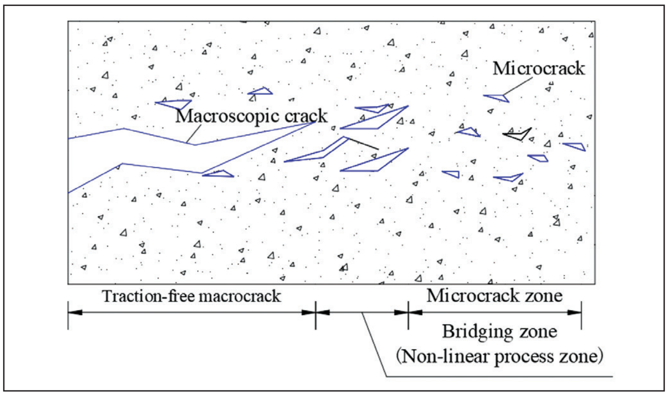

Figure 1: Schematic diagram of crack tip zoning

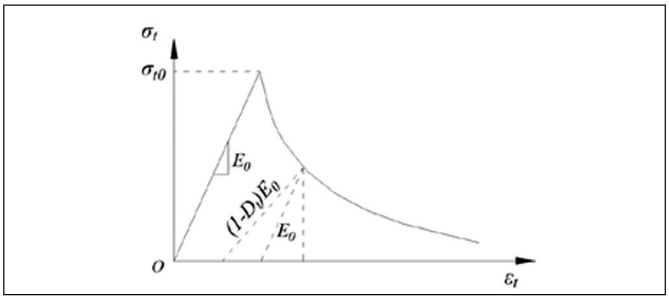

Figure 2: Uniaxial tensile stress-strain curve of concrete

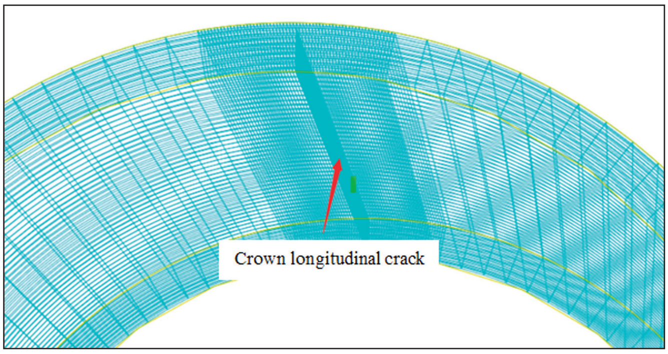

Figure 3: Numerical model of longitudinal crack in arch crown

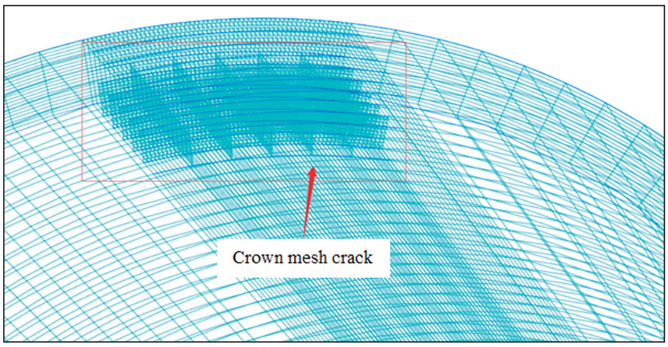

Figure 4: Numerical model of mesh crack in arch crown

Table 1: Physical and mechanical parameters of material

Material	γ (kN/m³)	μ	E_0 (GPa)	Tensile Strength (MPa)	Compressive Strength (MPa)
Concrete	23	0.2	31.5	2.4	23.4
Reinforcement	7850	0.2	200	210	210

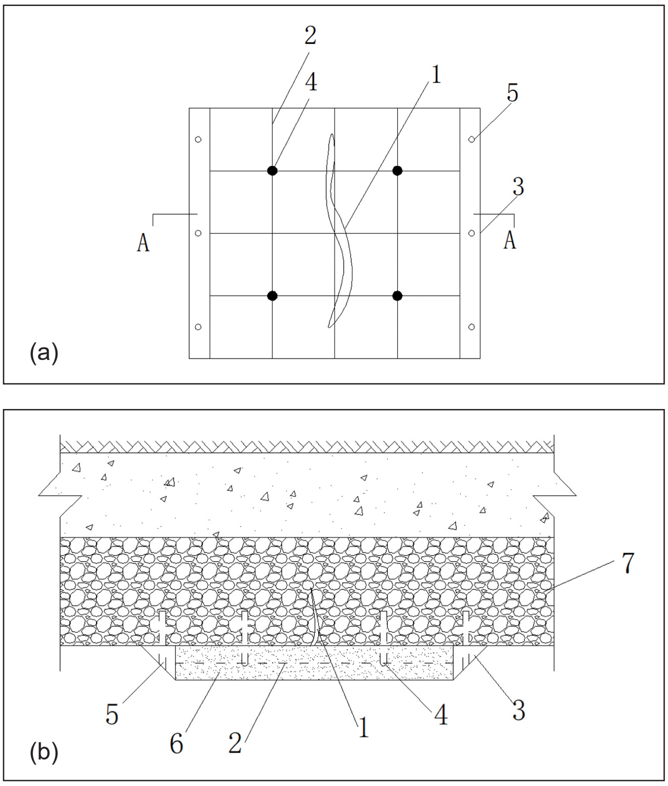

Figure 5: Structural diagram of face protection rebar
(a) Schematic diagram of the protective surface reinforcement in plan view;
(b) A-A sectional view
(1: Crack; 2: Protective Surface Reinforcement Steel; 3: Side Supporting Structure; 4: Reinforced Dowels; 5: Support Anchor Hole; 6: Mortar Protective Layer; 7: Lining)

The range of the protective surface reinforcement extends 1m beyond the crack range. In the stress analysis, the effect of the mortar protection layer is not considered, and the thickness of the shell elements is calculated equivalently based on the area. The schematic diagram of the reinforcement plan for the surface reinforcement is shown in Figure 5 (a), and the A-A cross-sectional view is shown in Figure 5 (b).

2.3 Material Physical and Mechanical Parameters

According to the *Railway Tunnel Design Code* (TB10003-2016), the elastic foundation parameters for IV-class surrounding rock are set to 350 MPa/m. The concrete strength grade is C35, and the type of reinforcement is HRB400. A plastic damage model is used for simulation. The damage evolution equation for concrete is determined based on the *Code for Design of Concrete Structures* (GB50010-2010) and (Li *et al.,* 2021; Zhang *et al.,* 2008). The material physical and mechanical parameters are shown in Table 1.

Table 2: Calculation Conditions

Crack Type	Characteristic Parameters
Single Longitudinal Crack	Length: 1m, 3m, 6m, 9m, 12m Depth: 0.1*H*, 0.5*H*, 0.9*H*
Mesh Cracks	Longitudinal Range: 0.5m, 1.0m, 1.5m Circumferential Range: 0.5m, 1.0m, 1.5m Depth: 0.5*H*

Note: H in the table indicates lining thickness

2.4 Calculation Conditions

First, the stress characteristics of single-line and double-line tunnel linings with a single longitudinal crack and mesh cracks at the vault are calculated and analysed. Then, based on the stress characteristics of the cracked linings, typical conditions are selected to analyse the reinforcement effect of the protective surface reinforcement. The calculation conditions are shown in Table 2.

3.0 THE STRESS CHARACTERISTICS OF CRACKED LINING STRUCTURES

The calculation results indicate that cracks have a negligible impact on the compressive load-bearing characteristics of the structure. Due to space limitations, only the tensile damage degree and the first principal stress calculation cloud diagrams for the conditions of a single longitudinal crack (9m long, 0.9H depth) and mesh cracks (1.5m longitudinal length, 1.5m circumferential width, 0.5H depth) at the crown of a single-line tunnel are presented here.

3.1 Single Longitudinal Crack

The calculation results of the tensile damage degree and the first principal stress of a single longitudinal crack (9m long and 0.5H depth) in a single-line tunnel are shown in Figure 6(a) and Figure 6(b).

The variation of the tensile damage degree of the lining in single-line and double-line tunnels with a single crack, as a function of crack length and depth, is shown in Figures 7 and 8.

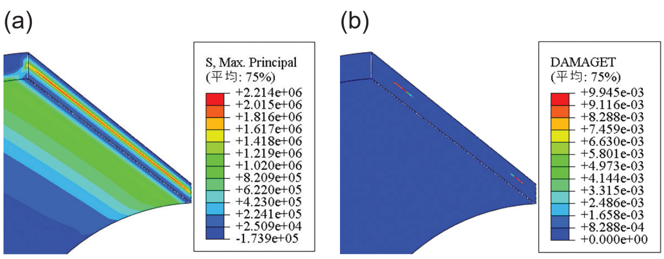

Figure 6: Calculation results of single line tunnel vault with longitudinal crack under typical working conditions
(a) the first principal stress of lining (Pa);
(b) lining tensile damage

As shown in Figure 6(a), the lining with a single longitudinal crack, under surrounding rock pressure, exhibits tensile damage at the crack tip along the crack's length, with a damage degree of 0.227. This indicates a tendency for the crack to propagate along its length. As shown in Figure 6(b), the first principal stress of the lining is 1.950MPa, which lies in the descending region of the stress-strain curve and is below the tensile strength of concrete. Therefore, in subsequent calculations and analyses, a tensile damage degree greater than 0 is used as the criterion for determining crack propagation.

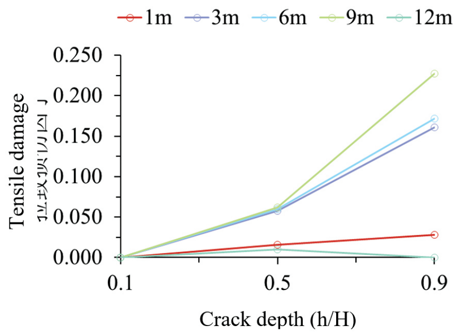

Figure 7: Relationship between tensile damage and longitudinal crack characteristic parameters of single track tunnel

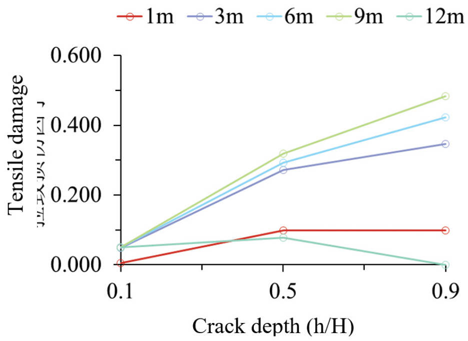

Figure 8: Relationship between tensile damage and longitudinal crack characteristic parameters of double track tunnel

As shown in Figures 7 and 8, for the single longitudinal crack scenario, increasing the crack depth results in a greater tensile damage degree, with damage concentrated at the crack tip. For cracks shorter than the lining's circumference (12m), longer cracks lead to a greater degree of tensile damage. When the crack length reaches 12m, stress release causes a reduction in the tensile damage degree of the structure. However, at this point, the crack significantly weakens the lining, and reinforcement measures equivalent to or stronger than those for non-longitudinal through cracks should be considered. For single-line tunnels, when the crack depth is 0.1H, the structural damage degree is 0, and the crack can be addressed with grouting closure or mortar surface treatment.

3.2 Mesh Crack

The tensile damage degree and the first principal stress calculation results for the condition of a mesh crack (1.5m longitudinal length, 1.5m circumferential width, 0.5H depth) in a single-line tunnel are shown in Figure 9(a) and Figure 9(b).

As shown in Figure 9 (a), for the lining structure with mesh cracks under the surrounding rock pressure, tensile damage occurs at the crack tips along the tunnel's direction, with a damage degree of 0.684, indicating that the mesh crack tends to propagate along the tunnel's direction. As shown in Figure 9 (b), the first principal stress of the lining is 1.929 MPa, which is in the descending part of the stress-strain curve and is below the tensile strength of concrete. The variation of the tensile damage degree of the lining in single-line and double-line tunnels with a single crack, as a function of crack length and depth, is shown in Figures 8 and 9.

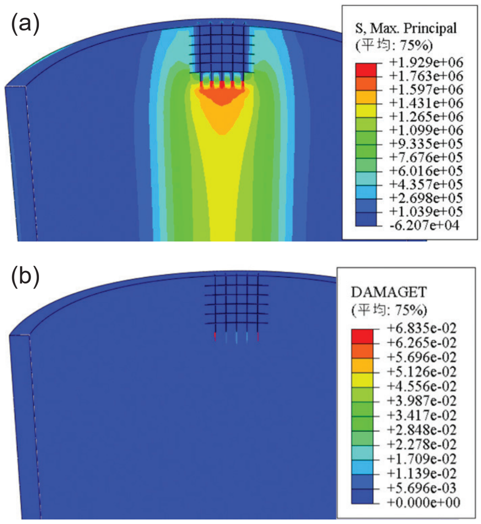

Figure 9: Calculation results of single line tunnel vault with mesh crack under typical working conditions (a) the first principal stress lining; (b) lining tensile damage

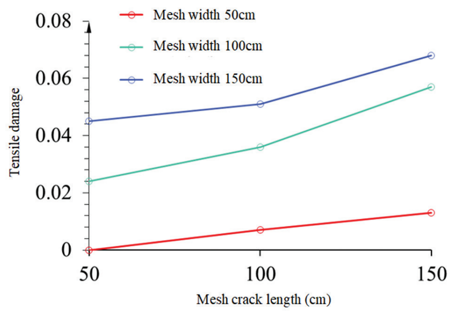

Figure 10: Relationship curve between tensile damage and mesh crack characteristic parameter of single track tunnel

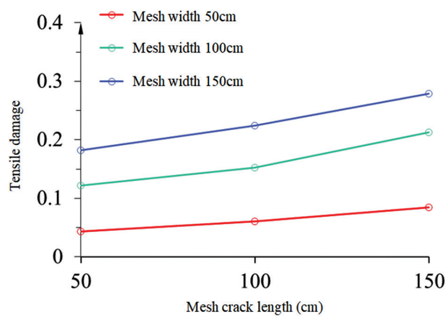

Figure 11: Relationship curve between tensile damage and mesh crack characteristic parameter of double track tunnel

As shown in Figures 10 and 11, for single-line and double-line tunnels with mesh cracks, the tensile damage degree of the lining is positively correlated with the longitudinal distribution length and circumferential distribution width of the mesh cracks. With an increase in the distribution range of the mesh cracks: The tensile damage degree of the lining structure with 0.5m×0.5m (longitudinal range × circumferential range) mesh cracks in single-line and double-line tunnels is 0 and 0.043, respectively. For a 1.5m×1.5m mesh crack, the tensile damage degree of the lining is 0.068 for single-line tunnels and 0.279 for double-line tunnels. In the case of single-line tunnels with a 0.5m×0.5m mesh crack, the tensile damage degree is 0, suggesting that the cracks can be treated with grouting or mortar coating alone.

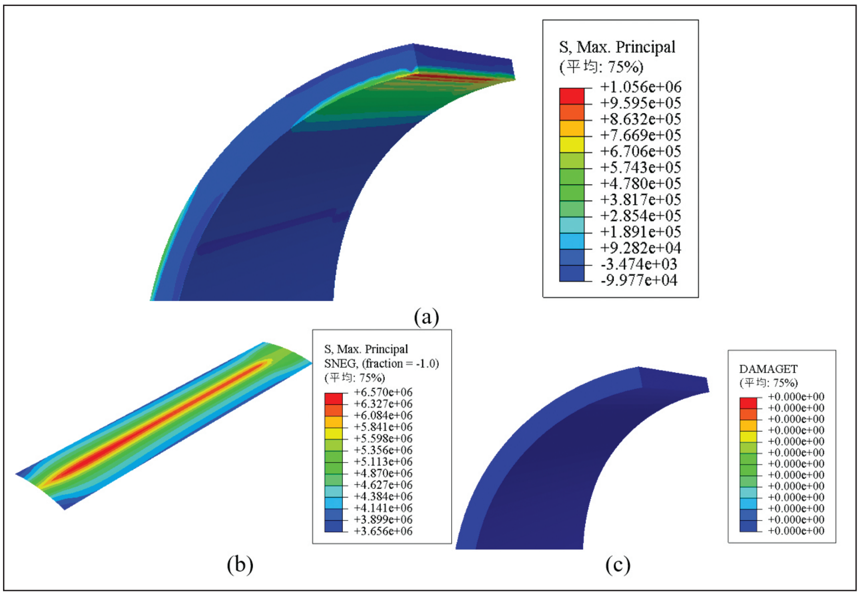

Figure 12: Calculation results of structural stress after surface reinforcement for typical single crack conditions
(a) the first principal stress of lining; (b) the first principal stress of the reinforcement; (c) lining tensile damage

4.0 THE REINFORCEMENT EFFECT OF SURFACE REINFORCEMENT MEASURES

Based on the results in Section 3, the structural damage degree of the lining under rock pressure is positively correlated with the crack length (<12m) and depth for single longitudinal cracks. For mesh cracks, the structural damage degree is positively correlated with the longitudinal and circumferential distribution ranges of the cracks. Therefore, for single longitudinal crack scenarios, simulations of the reinforcement effect of surface bars will be conducted for the most unfavourable and special conditions, with crack lengths of 9m and 12m, and depths of 0.1H, 0.5H, and 0.9H. For mesh crack scenarios, reinforcement effect simulations will be conducted for crack dimensions of 0.5m×0.5m, 1.0m×1.0m, and 1.5m×1.5m. The reinforcement bar diameter is set at φ10mm, with longitudinal and circumferential spacing both set at 150mm.

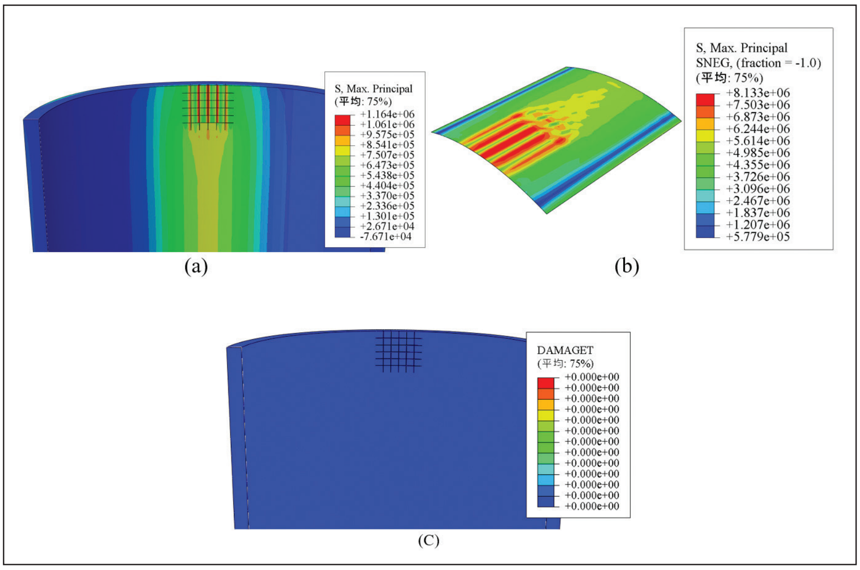

Figure 13: Calculation results of structural stress after surface reinforcement for typical mesh crack conditions
(a) the first principal stress of lining; (b) the first principal stress of the reinforcement; (c) lining tensile damage

Due to space limitations, only the cloud diagrams of calculation results for the single-track tunnel with a single longitudinal crack (length 9m, depth 0.5H) and the single-track tunnel with mesh cracks (1.5m × 1.5m) are presented here, as shown in Figures 12 and 13 respectively.

As shown in Figures 12(a) and 13(a), for the single longitudinal crack condition (length 9m, depth 0.5H) and the mesh crack condition (1.5m × 1.5m) in the single-track tunnel, the application of surface reinforcement eliminates tensile damage in the lining. The maximum principal stress in the lining is 1.056 MPa and 1.164 MPa, respectively, located on the surface near the cracks. According to the *Railway Tunnel Design Code* (TB10003-2016), the structural safety factors are 3.977 and 3.608, respectively, meeting the code's requirements. As shown in Figures 12(b) and 13(b), the maximum principal stress in the surface reinforcement is 6.570 MPa and 8.133 MPa, which are far below the design strength of 210 MPa. Thus, the use of surface reinforcement effectively enhances the structural bearing capacity, and the reinforcement effect complies with the requirements of the *Railway Tunnel Design Code*. As shown in Figures 12(c) and 13(c), the tensile damage degree at the tip of the lining for both single cracks and mesh cracks is 0 after reinforcement with surface reinforcement.

Table 3: Calculation results of reinforcement effect of surface reinforcement on lining with single longitudinal crack

Section Type	Crack Length	Crack Depth	Unreinforced			Surface Reinforcement			
			Tensile Damage	Lining First Principal Stress (MPa)	SF	Tensile Damage	Lining First Principal Stress (MPa)	First Principal Stress of the Surface Reinforcement (MPa)	SF
Single Line	9	0.1*H*	0	1.58	2.658	0	0.806	5.444	5.211
	12	0.1*H*	0	1.58	2.658	0	0.802	5.823	5.237
	9	0.5*H*	0.062	2.218	—	0	1.056	6.57	3.977
	12	0.5*H*	0.01	2.214	—	0	0.995	6.187	4.221
	9	0.9*H*	0.227	1.95	—	0	1.061	6.565	3.959
	12	0.9*H*	0	1.33	—	0	1.061	6.564	3.959
Double Line	9	0.1*H*	0.05	1.782	—	0	0.994	6.628	4.225
	12	0.1*H*	0.05	1.782	—	0	0.964	6.629	4.357
	9	0.5*H*	0.319	2.044	—	0	1.221	7.593	3.440
	12	0.5*H*	0.078	1.958	—	0	1.221	7.593	3.440
	9	0.9*H*	0.484	2.041	—	0	1.227	7.591	3.423
	12	0.9*H*	0	1.512	—	0	1.227	7.591	3.423

Table 4: Calculation results of reinforcement effect of surface reinforcement on lining with mesh crack

Section Type	Longitudinal Range	Circumferential Range	Unreinforced			Surface Reinforcement			
			Tensile Damage	Lining First Principal Stress (MPa)	SF	Tensile Damage	Lining First Principal Stress (MPa)	First Principal Stress of the Surface Reinforcement (MPa)	SF
Single Line	0.5m	0.5m	0	1.981	2.120	0	1.028	7.782	4.086
	1.0m	1.0m	0.036	2.012	—	0	1.066	8.196	3.940
	1.5m	1.5m	0.068	1.929	—	0	1.164	8.133	3.608
Double Line	0.5m	0.5m	0.043	2.183	—	0	1.128	9.609	3.723
	1.0m	1.0m	0.153	2.234	—	0	1.247	8.923	3.368
	1.5m	1.5m	0.279	2.233	—	0	1.237	9.239	3.395

Note: "—" indicates that when there is tensile damage to the lining, the first principal stress is in the descending stage, so the value of the first principal stress and the safety factor is not of reference significance

The stress calculation results under rock pressure for single-track and double-track tunnel linings with single longitudinal cracks and mesh cracks after reinforcement with surface reinforcement are shown in Tables 3 and 4.

As shown in Tables 3 and 4, when 50% of the surrounding rock pressure is taken as the design load, the reinforced lining with φ10mm@150mm surface reinforcement does not exhibit any tensile damage in both the single longitudinal crack and the mesh crack cases, indicating that the surface reinforcement can effectively inhibit the further expansion of the cracks. For the most unfavourable condition of single cracks in both single-line and double-line tunnels, the tensile stress of the lining is 1.061 MPa and 1.227 MPa, respectively, distributed near the cracks on the inner surface of the lining. The safety factors are 3.959 and 3.423, respectively. Although some conditions do not meet the required safety factor of 3.6, the deviation is less than 10%, indicating that surface reinforcement can effectively reduce stress concentration at the crack tip and improve the structural bearing capacity.

For the most unfavourable condition of mesh cracks in both single-line and double-line tunnels, the tensile stress of the lining is 1.164 MPa and 1.237 MPa, respectively, distributed near the crack on the inner surface of the lining. The corresponding safety factors are 3.608 and 3.395. In some conditions, the safety factor does not meet the required 3.6, but it is less than 10% away from 3.6, indicating that the surface reinforcement can effectively improve the stress concentration at the crack tip and enhance the structural bearing capacity.

It should be noted that for cracks with a depth of 0.9H, from the perspective of inhibiting crack propagation, the surface reinforcement is beneficial. However, for cracks that are about to penetrate, it is necessary to consider potential failure modes such as shear failure and misalignment due to insufficient shear strength at that location. Surface reinforcement is suitable for crack opening failure modes, but its effect on the lining's shear strength is relatively weak. Additionally, the load mode that results in a crack with a depth of 0.9H differs from the design load mode, making it difficult to analyse. Therefore, surface reinforcement is deemed unsuitable for cracks with a depth of 0.9H. For safety reasons, cracks with depths between 0.5H and 0.9H, as well as those with a depth of 0.9H, are grouped together, and in such cases, surface reinforcement is not considered applicable. The first principal stress of the surface reinforcement in the above-mentioned conditions ranges from 5.444 MPa to 9.609 MPa, which is far below the design strength of HRB400 steel bars (210 MPa), indicating that the surface reinforcement remains structurally sound.

5.0 CONCLUSIONS AND RECOMMENDATIONS

This paper uses finite element software to conduct a numerical analysis on the reinforcement effect of cracked lining with surface reinforcement under 50% surrounding rock load. The main conclusions are:

- The first principal stress distribution range of the surface reinforcement components is 5.444 MPa to 9.609 MPa, far lower than the design strength of 210 MPa, indicating that the surface reinforcement will not fail.
- No tensile damage was observed in any of the cracked lining conditions, indicating that the surface reinforcement effectively inhibits the expansion of cracks.
- For linings with single and mesh cracks, the surface reinforcement effectively improves the stress concentration at the crack tips, reduces the tensile stress in the structure, and increases the structure's safety factor, making it an effective crack reinforcement measure.
- Considering the shear failure mode of cracks deeper than 0.5H, the weaker shear resistance of the surface reinforcement, and the complexity of the formation mechanism, surface reinforcement is considered unsuitable for reinforcing cracks of this depth.

Additionally, this paper looks into the reinforcement effect of surface reinforcement in the repair of plain concrete cracks and confirms its effectiveness in crack remediation. However, the stability of surface reinforcement under train-induced wind in high-speed railway tunnels has not been studied yet. This will be further explored in subsequent research to determine the feasibility of surface reinforcement in the remediation of lining cracks in high-speed railway tunnels. ■

AUTHORS' CONTRIBUTIONS

- **Qizhu Jiao:** Conceptualisation, study design, and supervision.
- **Yalong Shi:** Writing original draft preparation and literature review.
- **Congwen Yan:** Data collection, methodology, and formal analysis.
- **Peng Chen:** Data validation, visualisation, and software implementation.
- **Kai Liu:** Writing review, editing, and final manuscript approval.

REFERENCES

[1] Cangshu, L. (2018). *Research on distribution and safety evaluation in lining split of high speed railway tunnel based on statistical analysis* (Doctoral dissertation). Beijing Jiaotong University.

[2] Wei, W., Jun, D., & Juntao, Y. (2016). Research on safety of lining structure in railway tunnel under spatial crack disease. *Journal of Safety Science and Technology, 12*(1), 33–37. https://doi.org/10.11731/j.issn.1673-193x.2016.01.006

[3] Hualao, W., Xuezeng, L., Ning, L., & Dongwu, X. (2010). Safety evaluation of tunnel lining with longitudinal cracks and reinforcement design. *Chinese Journal of Rock Mechanics and Engineering, 29*(Z1), 2651–2656. CNKI:SUN:YSLX.0.2010-S1-013

[4] Jingwen, Y., Lun, G., Zichao, X., Shifu, W., Xingxing, L., & Xuhao, C. (2017). Analysis of stress state of assembly structure for rapid repair of lining cracking in traffic tunnels. *Subgrade Engineering, (4)*, 123–127. https://doi/10.13379/j.issn.1003-8825.2017.04.25

[5] Jiang, C., Junsheng, Y., Nengxue, C., & Xiaowen, X. (2014). Study on crack remediation and reinforcement of lining in railway tunnel. *Journal of Safety Science and Technology, 10*(9), 134–139. https://doi.org/10.11731/j.issn.1673-193x.2014.09.023

[6] Chenhong, S., Nannan, A., & Zhifeng, W. (2020). Study on crack remediation and reinforcement of lining in railway tunnel. *Journal of Architecture and Civil Engineering, 37*(5), 203–213. https://doi.org/10.19815/j.jace.2020.08029

[7] Hongqian, Y., Jun, Q., Huairong, L., Zhigang, H., & Deiwu, L. (2021). Study on causes and treatment of concrete cracking of the secondary lining of Qilianshan Tunnel. *Modern Tunnelling Technology, 58*(1), 217–222. https://doi.org/10.13807/j.cnki.mtt.2021.01.029

[8] Donghua, S. (2019). Study on defect correction technology for tunnel lining in high-speed rail line. *Railway Construction Technology, (Z1),* 113–117. https://doi.org/10.3969/j.issn.1009-4539.2019.S1.027

[9] Zhijie, W., Haiyan, X., Ping, Z., Qichao, Z., &Xiao, G. (2017). Study on the treatment of lining defects of highway tunnel. *Railway Standard Design, 61*(10), 125–132. https://doi.org/10.13238/j.issn.1004-2954.2017.10.025.

[10] Ministry of Housing and Urban-Rural Development of the People's Republic of China. (2010). *GB 50010-2010 code for design of concrete structures.* China Architecture Publishing & Media Co., Ltd.

[11] Qingfu, L., Yihang, K., & Wei, G. (2021). CDP model parameters calculation and value method verification. *Journal of Zhengzhou University (Engineering Science), 42*(2), 43–48. https://doi.org/10.13705/j.issn.1671-6833.2020.06.002

[12] Jin, Z., Qing, W., Shouying, H., & Chuanjia, W. (2008). Parameter verification of concrete damage plasticity model in ABAQUS. *Building Structure, 38*(8), 127–130. https://xueshu.baidu.com/usercenter/paper/show?paperid=99ceb6e61f30a4480852d4b35e3735cf

PROFILES

QIZHU JIAO is currently employed by China Railway Fourth Survey and Design Institute Group Co., Ltd. He obtained a Bachelor's degree in Underground Engineering and Tunnel Engineering from Tongji University in 1992, and a Master's degree in Architecture and Civil Engineering from Huazhong University of Science and Technology in 2006. Since 1992, he has been long engaged in the design and research of tunnel engineering. He has presided over multiple railway, highway and municipal tunnel projects with a total length of more than 2,000 kilometers. His projects have won one FIDIC Project Award, one China National Science and Technology Progress Award, and five Provincial/Municipal Science and Technology Progress Awards.
Email address: 415884709@qq.com

YALONG SHI is a Senior Engineer at the China Railway Southwest Research Institute. He received his Master’s degree from the China Academy of Railway Sciences in 2014. His work focuses on tunnel and underground engineering, as well as advanced monitoring and measurement technologies for urban rail transit. He has made significant contributions to the development and application of intelligent monitoring technologies, and his research achievements have been recognized with the Second Prize of the Science and Technology Progress Award of China Railway Group and the Second Prize of the Chengdu Municipal Science and Technology Progress Award.
Email address: shiyalong_crsi@163.com

CONGWEN YAN is employed by China Railway Fourth Survey and Design Institute Group Co., Ltd. He obtained a Master's degree in Architecture and Civil Engineering from Southwest Jiaotong University in 2020, and a Bachelor's degree in Civil Engineering from the same university in 2017. Currently, he is engaged in the design of railway tunnel engineering.
Email address: 1162719639@qq.com

PENG CHEN is an Engineer at China Railway Southwest Research Institute Co., Ltd. He obtained his master's degree from Southwest Jiaotong University in 2018. His main research focuses on structural safety assessment and defect remediation of tunnels and underground engineering.
Email address: chenpeng_crsi@163.com

KAI LIU is an Engineer at China Railway Southwest Science Research Institute Co., Ltd. He obtained a master's degree in Architecture and Civil Engineering from Southwest Jiaotong University in 2019. He is now engaged in research and consulting work on the detection and remediation of tunnel defects in operation, which is one of the key areas of research in the industry. He has unique insights and research on tunnel lining cracks and voids in operational tunnels.
Email address: 513290132@qq.com