19th Australasian Tunnelling Conference – Acosta-Martínez, Stewart and Hudson-Smith (Eds.)
 ISBN 978-0-85825-002-4

Research on the mechanism of shotcrete support based on the combined effect of rock-shotcrete

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ABSTRACT: The most significant feature of shotcrete is its ability to tightly adhere to the surrounding rock, thereby forming a load-bearing composite structure between shotcrete and loose rock blocks. To quantitatively analyze this complex mechanism, we derived the theoretical bearing capacity by analyzing the cross-sectional stress-strain relationship of the composite structure composed of shotcrete and loose rock blocks. By adopting the principle of equivalent fracture energy, we fitted post-peak test data of bond stress at the rock-shotcrete interface and established an interface mechanical model. Based on this model, the discontinuous deformation analysis (DDA) method was employed to simulate the composite structure. The research demonstrates that shotcrete significantly enhances the bearing capacity of the rock-shotcrete composite through interfacial bonding. Furthermore, the mechanical properties of the rock-shotcrete interface directly influence the failure mode of the composite structure.

1 INTRODUCTION

In tunnel engineering with severe structural cutting, there is a possibility of local loosening and collapse of multiple rock blocks. After the application of shotcrete, the relative sliding and loosening of the rock blocks can be prevented by the bonding force between the shotcrete and the rock blocks, resulting in a certain range of shotcrete and block rock forming a whole that can bear pressure. Therefore, the key to analyzing the shotcrete support for multiple rock blocks is to clarify how its interfacial bonding effect mobilizes the joint bearing capacity of the rock blocks. In response to this, scholars have conducted research from different directions. For example, Bernard, E.S. et al. summarized the important role of rock-shotcrete bonding performance in the support of fiber shotcrete [1], Zhang, P. et al. studied the interaction between rock mass and shotcrete through numerical simulation [2], Dong, W. and Dong, X. et al. studied the mechanical properties of the rock-shotcrete interface through DIC technology and numerical simulation [3, 4], Sjölander, A. et al. studied the influence of rock-shotcrete bonding strength and shotcrete thickness on the support effect [5, 6], and Chang, Y. et al. studied the support effect of rock-shotcrete interface bonding performance on a single moving rock mass[7]. On the basis of the above research, this article quantitatively analyzes the supporting mechanism of the overall load-bearing structure formed by the bonding between shotcrete and rock blocks, and verifies it through simulation using discontinuous deformation method.

2 MECHANICAL ANALYSIS OF SHOTCRETE SUPPORT BASED ON ROCK-SHOTCRETE COMPOSITE EFFECT

If the bonding effect between shotcrete and rock is not considered in the research, and it is only regarded as a simple resistance structure, and loose rock blocks are completely regarded as loads, then the stress analysis of shotcrete is to regard it as a bending thin plate under uniformly distributed loads. When the tensile stress on the lower side of the thin plate reaches the ultimate tensile strength of the material, the support cracks and fails. Therefore, the flexural bearing capacity M_{R1} of shotcrete support without considering interface bonding can be obtained by the following equation:

$$M_{R1} = f_{pt} \times t^2/6 \tag{1}$$

In the equation, f_{pt} is the tensile strength of shotcrete material, and t is the thickness of the shotcrete layer.

But if the bonding effect between shotcrete and rock is considered, and shotcrete and rock blocks are regarded as a whole structure composed of bonding effect, then the thickness of the structure can be equivalent to the sum of the height of the rock block and the thickness of the shotcrete, as shown in Figure 1.

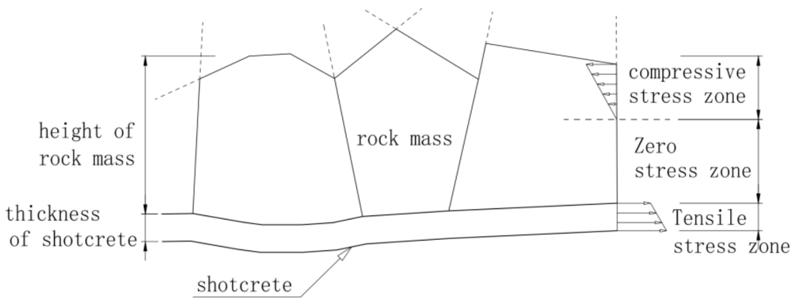


Figure 1. A shared load-bearing structure composed of shotcrete and multiple rock blocks

In this structure, compressive stress can be transmitted between rock blocks, but tensile stress cannot be transmitted. The tensile stress is borne by the shotcrete adhered to the bottom surface of the rock blocks. At the same time, the entire structure is still considered to satisfy the assumption of a plane section during the analysis process.

According to the assumption of a flat section and the axial force balance equation of the section, the height x of the compressive stress zone can be calculated as:

$$x = -\lambda \cdot t + \sqrt{\lambda^2 \cdot t^2 + 2\lambda \cdot t \cdot (b + t/2)} \tag{2}$$

In the equation, b is the height of the rock mass jointly carried by the shotcrete, t is the thickness of the shotcrete, $\lambda = E_p/E_c$, E_c is the elastic modulus of the rock, and E_p is the elastic modulus of the shotcrete.

When the overall structural bearing capacity is controlled by the strength of the shotcrete material at the lower edge of the section, the flexural bearing capacity M_{R2} of the support considering interface bonding can be obtained by the following equation:

$$M_{R2} = f_{pt} \cdot \left(1 + \frac{b-x}{b-x+t}\right) \cdot \frac{t}{2} \cdot \left[\left(b - x + \frac{t}{2}\right) + \frac{2x}{3}\right] \tag{3}$$

When the overall structural bearing capacity is controlled by the bonding strength of the rock-shotcrete interface, the bending bearing capacity M_{R3} of the support considering the interface bonding can be obtained by the following equation:

$$M_{R3} = f_{lt} \cdot \left(1 + \frac{b-x+t}{b-x}\right) \cdot \frac{t}{2} \cdot \left[\left(b - x + \frac{t}{2}\right) + \frac{2x}{3}\right] \tag{4}$$

In the equation, flt represents the strength of the rock-shotcrete interface.

Given the significant impact of the bonding performance of the rock-shotcrete interface on the support effect of shotcrete in the above mechanical analysis, it is necessary to establish a mechanical model for the interface between shotcrete and rock in order to quantitatively calculate the support capacity of shotcrete.

3 MECHANICAL MODEL OF THE INTERFACE BETWEEN SHOTCRETE AND ROCK

Due to the complex factors such as physical interlocking and chemical bonding involved in the composition of rock-shotcrete interface performance, it is not possible to simply describe it using concepts from elastic mechanics. Therefore, it is necessary to construct corresponding models for crack initiation and damage evolution for analysis. Therefore, based on the damage bonding model as the mechanical model for the interface performance of rock-shotcrete, the interface failure is divided into two stages. In the initial stage of tension, the interface is in an elastic state, and the bond stress and interface opening displacement are linearly related, with the ratio being the elastic bond stiffness; When the bonding stress reaches its peak, the interface transitions to the plastic softening stage, and the degree of damage to the bonding stiffness is defined by the damage factor ω, which is a single value function of the opening displacement. The specific mechanical model concept is shown in Figure 2, and the mechanical model function is shown in equation (5).

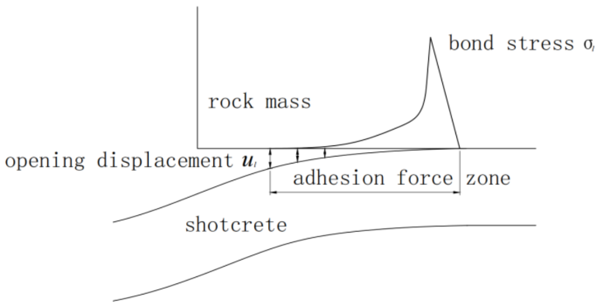


Figure 2. Conceptual diagram of the rock-shotcrete interfacial damage bonding model

$$\sigma_l(u_l)=\begin{cases} k\cdot u_l & u_l \le u_{l0} \\ k(1-\omega)\cdot u_l & u_l > u_{l0} \end{cases} \tag{5}$$

In the equation, σ_l is the bond stress, u_l is the opening displacement, k is the elastic bond stiffness, ω is the damage factor, and u_{l0} is the opening displacement corresponding to the peak bond stress.

According to the tensile test of the bond between shotcrete and rock, the natural exponential function is used to fit the post peak curve, and the stress opening displacement function relationship can be expressed as follows:

$$\sigma_l(u_l)=\sigma_{lf}\cdot e^{-\left(\frac{u_l-u_{l0}}{u_{lf}-u_{l0}}\right)} \qquad u_l > u_{l0} \tag{6}$$

In the equation, σ_{lf} is the peak value of bond stress, u_{lf} is the characteristic value of post peak opening displacement defined, and its product with the peak value of bond stress σ_{lf} is equal to the post peak fracture energy of the test. The definition of Ulf is shown in Figure 3, where G'_{lf} represents the post peak fracture energy.

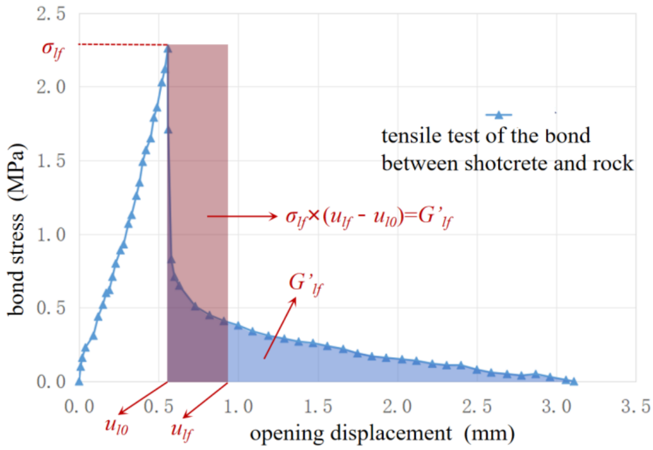


Figure 3. Definition of characteristic post-peak opening displacement based on the principle of equivalent fracture energy

By solving equations (1) and (2) together, the damage factor ω can be obtained as:

$$\omega(u_l) = 1 - \frac{u_{l0}}{u_l} \cdot e^{-\left(\frac{u_l - u_{l0}}{u_{lf} - u_{l0}}\right)} \qquad u_l > u_{l0} \tag{7}$$

4 SIMULATION ANALYSIS OF SHOTCRETE SUPPORT CONSIDERING ROCK-SHOTCRETE INTERFACE BONDING

To further analyze the impact of interface bonding failure on the effectiveness of shotcrete support, the discontinuous deformation analysis method (DDA) was used to simulate the process of shotcrete support failure under the action of a single rock block. In DDA simulation calculations, the previously fitted rock-shotcrete interface mechanics model equation (5) is used as the interface bonding constitutive model. The parameters of the rock mass and shotcrete materials are shown in Tables 1 and 2:

Table 1. Material parameters for simulation of rock block and rock-shotcrete interface

Project		Parameter value	Unit
rock mass	compressive strength	40	MPa
	tensile strength	2.4	MPa
	deformation modulus	40	GPa
	Poisson's ratio	0.2	/
	density	2.2	t/m^3

Table 2. Material parameters for shotcrete simulation

Project		Grade of Shotcrete					
		C40	C60	C80	UC100	UC120	UC160
shot-crete	compressive strength	40MPa	60MPa	80MPa	100MPa	120MPa	160MPa
	tensile strength	2.39MPa	2.85MPa	3.11MPa	5MPa	7MPa	9MPa
	elastic modulus	32.5GPa	36.5GPa	38GPa	40GPa	40GPa	45GPa
	Poisson's ratio	0.2	0.19	0.18	0.17	0.16	0.15

The model consists of shotcrete and multiple rock blocks, with a span of 4m and a height of 0.5m. The shotcrete layer tightly adhered below is 0.08m thick. The boundary conditions at both ends of the model are contact boundaries, simulating the surrounding intact rock mass wrapping. Apply uniformly distributed load on the top of the rock block and gradually increase it in the calculation. The specific calculation model is shown in Figure 4.

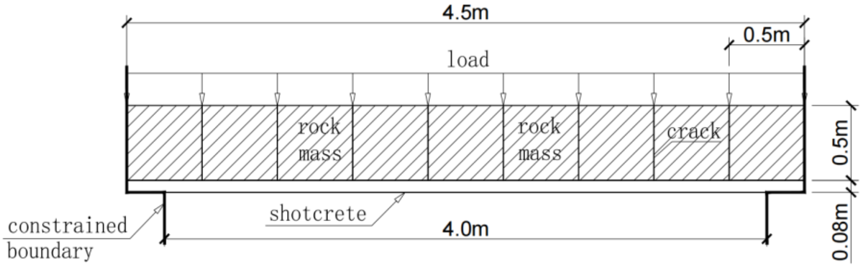
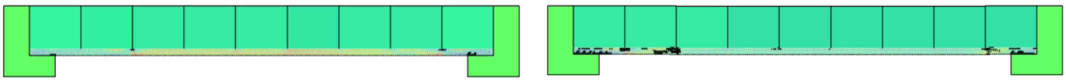


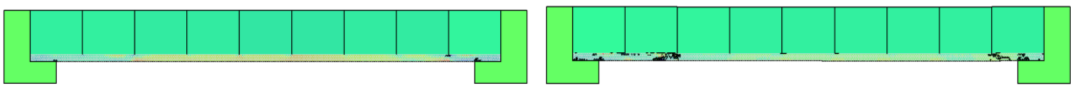
Figure 4. DDA simulation model of joint support of shotcrete and rock blocks

When using C40 shotcrete to support rock masses, the failure first occurs at the top of the shotcrete layer, as shown in Figure 5 (a). At this time, there is no obvious debonding at the rock-shotcrete interface, and the initial failure is the shear failure starting from the top of the shotcrete. As the load increases, the number of damage locations on the top of the shotcrete increases, and the cracks gradually extend from top to bottom until the load cannot continue to increase, as shown in Figure 5 (b). Therefore, under this calculation model, the failure of C40 shotcrete material occurs before the failure of the rock-shotcrete interface, and increasing the shotcrete grade is an effective means of enhancing support.



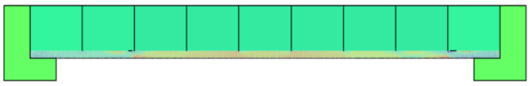
(a) Initial strength failure of shotcrete (b) Expansion of strength failure range of shotcrete
Figure 5. Simulation analysis of C40 shotcrete and rock block combination

When using C60 shotcrete to support rock masses, the initial failure is also shear failure starting from the top of the shotcrete, with cracks extending from top to bottom. The failure mode is basically the same as C40 shotcrete support, as shown in Figure 6.

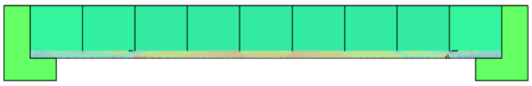


(a) Initial strength failure of shotcrete (b) Expansion of strength failure range of shotcrete
Figure 6. Simulation analysis of C60 shotcrete and rock block combination

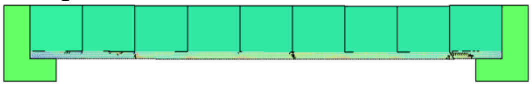
When using C80 shotcrete to support rock masses, the first failure that occurs is the debonding of the rock-shotcrete interface. At this time, the shotcrete material has not yet undergone significant damage, as shown in Figure 7 (a). As the load increases, interface debonding occurs, leading to tensile failure at the bottom, as shown in Figure 7 (b). As the load continues to increase, the number and range of interface debonding locations increase, and the cracks gradually penetrate the support section from below to above, as shown in Figure 7 (c). Therefore, under this calculation model, the rock-shotcrete interface failure has already occurred before the C80 shotcrete material failure.



(a) Initial interface debonding of shotcrete



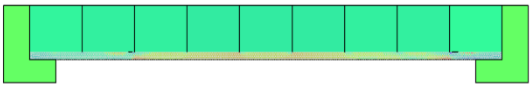
(b) The detachment of shotcrete interface leads to tensile damage at the bottom



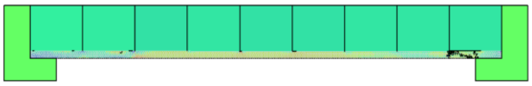
(c) Interface debonding and expansion of tensile failure range of shotcrete

Figure 7. Simulation analysis of C80 shotcrete and rock block combination

When using UC100 shotcrete to support rock masses, the failure mode is entirely governed by the rock-shotcrete interfacial failure. When the interface debonding range has extended to a larger range, the shotcrete will cause tensile damage to the bottom, as shown in Figure 8.



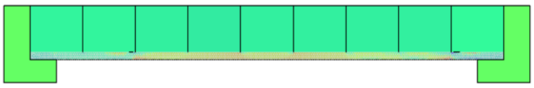
(a) Initial interface debonding of shotcrete



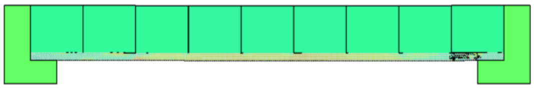
(b) Interface debonding and expansion of tensile failure range of shotcrete

Figure 8. Simulation analysis of UC100 shotcrete and rock block combination

When using UC120 shotcrete or even stronger UC160 to support rock masses, the form and position of support failure are basically the same as those of UC100, as shown in Figures 9 and 10. At this time, the bonding strength of the rock-shotcrete interface is the controlling factor for failure, and the high performance of the material itself is not fully utilized.

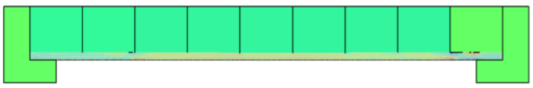


(a) Initial interface debonding of shotcrete

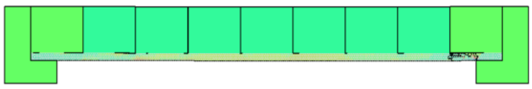


(b) Interface debonding and expansion of tensile failure range of shotcrete

Figure 9. Simulation analysis of UC120 shotcrete and rock block combination



(a) Initial interface debonding of shotcrete



(b) Interface debonding and expansion of tensile failure range of shotcrete

Figure 10. Simulation analysis of UC160 shotcrete and rock block combination

Figure 11 shows the load displacement curve of shotcrete and rock mass simulation analysis. It can be seen from the figure that when the shotcrete grade is lower than C80, the support failure is controlled by the material strength. Therefore, the higher the grade, the stronger the support bearing capacity. When the shotcrete grade is higher than UC100, the support failure is controlled by the bonding strength of the rock-shotcrete interface. Continuing to increase the shotcrete grade has limited effect on enhancing the support. The load displacement curves of UC100, UC120, and UC160 shotcrete supports are basically the same.

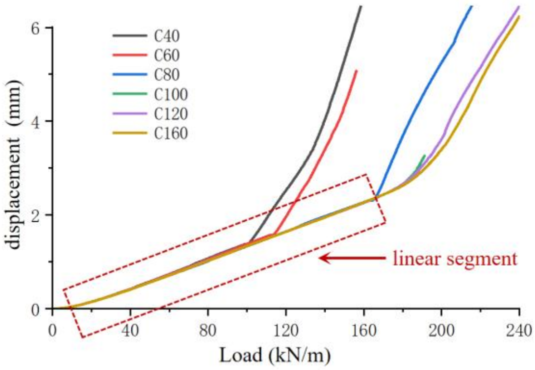


Figure 11. Load displacement curve of shotcrete and rock mass simulation analysis

In Section 1, the theoretical flexural bearing capacity expressed by equations (3) and (4) was obtained through cross-sectional analysis of a joint load-bearing structure composed of shotcrete and rock masses. Therefore, the linear segment bearing capacity calculated by DDA simulation (as shown in Figure 11, the maximum load of each labeled shotcrete linear segment) was converted into the bearing capacity of a 4m span simply supported beam and compared with the theoretical value to verify the results of the two analysis methods, as shown in Figure 12.

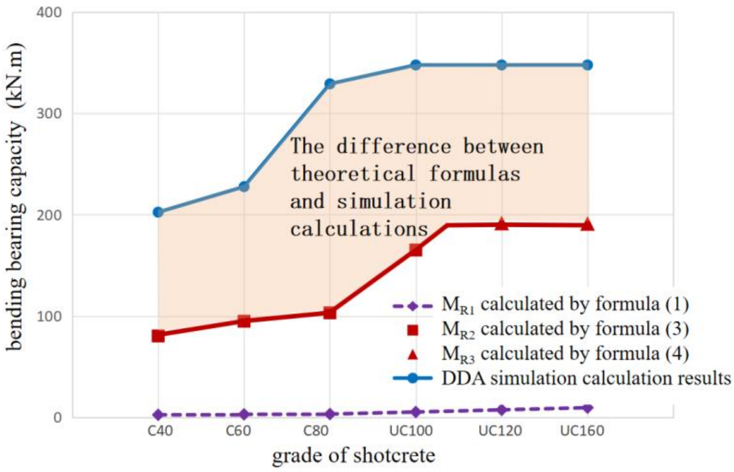


Figure 12. Flexural bearing capacity of shotcrete support with different grades

As shown in Figure 12, the theoretical equations and simulation calculations demonstrate that the failure modes of each grade of concrete support are basically the same, and the trend of change is consistent. A support model that only considers the resistance of shotcrete itself will seriously underestimate the support effect of shotcrete; When the shear strength of the rock-shotcrete interface remains unchanged, the flexural bearing capacity of the overall rock-shotcrete structure begins to be controlled by the interface strength after the shotcrete grade is increased to UC100. Increasing the strength of the shotcrete material has limited impact on the support effect; Only by increasing the strength of strong shotcrete materials without damaging the rock-shotcrete interface can the thickness of shotcrete be effectively reduced. At the same time, in the simulation calculation, the two sides of the loose rock block are constrained by the simulated intact rock mass, further improving the bearing capacity of the rock block combination, namely the Voussoir Beam effect. Therefore, the simulated bending bearing capacity is significantly higher than the theoretical equation, and the degree of improvement of each label is basically the same.

5 CONCLUSIONS

This article studies the mechanism of shotcrete support based on rock-shotcrete combination effect through theoretical analysis and numerical simulation. The main conclusions are as follows:

1) The damage bonding model established based on the principle of equivalent fracture energy through rock-shotcrete interface tests can better reflect the mechanical properties of the interface from cracking to debonding, providing a basis for quantitative analysis of rock-shotcrete composite structures.
2) The mechanical properties of the rock-shotcrete interface not only determine the failure mode of shotcrete support, but also affect the resistance performance of shotcrete materials. When the adhesion force is maintained, the failure of shotcrete will be controlled by its shear resistance. Only when shotcrete first peels off from the rock and loses its adhesion force, bending failure becomes possible.
3) A support model that only considers the resistance of shotcrete itself will seriously underestimate the support effect of shotcrete. In addition to its own material resistance, shotcrete can prevent relative sliding and loosening of rock blocks through its bonding force with the contact surface, resulting in the formation of a load-bearing whole between shotcrete and block shaped rock mass within a certain range. Due to the improvement of integrity, the Voussoir Beam effect of rock blocks becomes more significant compared to the unsupported condition.
4) Comparing the results of discontinuous deformation simulation analysis (DDA) and theoretical equation calculation of the bearing capacity of rock-shotcrete composite structures, it can be seen that the failure modes of each grade of concrete support obtained by the two methods are basically the same, and the trend of bending bearing capacity changes of the two methods is consistent, which can mutually confirm the mechanism of shotcrete support based on the rock-shotcrete composite effect.

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