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Investigation of composite shell lining interface behavior of rock tunnel

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ABSTRACT: The utilization of sprayed membranes facilitates the creation of a composite effect between shotcrete and sprayed membranes within tunnel linings. Nevertheless, the mechanism governing the composite shell lining remains indistinct. Through the employment of laboratory testing methodologies, shear compression tests were executed on specimens featuring varying core angles and sprayed membranes to ascertain the adhesive strength, internal friction angle, and shear stiffness of the sprayed membranes. The ultimate tensile compressive shear strength envelope was subsequently generated, serving as the threshold for the interfacial anti-slip strength. Furthermore, the normal stress and shear stress at each point along the interface were derived via numerical simulation, and an assessment was conducted to determine if each stress surpassed the strength envelope line, thereby establishing whether the interface experienced misalignment.

1 GENERAL INTRODUCTION

Upon the application of spray waterproofing featuring high double-sided bonding strength, in conjunction with the utilization of permanent shotcrete as the initial and subsequent layers of shotcrete, the synergistic interaction between these layers allows for the conceptualization of the first and second layers of shotcrete as a unified composite structure, namely a composite shell lining [1].

Despite the issuance of the "ITAtech Design Guidance For Spray Applied Waterproofing Membranes"[2] by the International Tunneling Association in 2013, intended to provide guidance and standardization for the application of this technology, it did not offer a definitive calculation methodology for the stress exerted upon the lining structure, nor did it include empirical parameter data. Reference [3] delves into the stress state and potential failure mechanisms of spray membrane interfaces, as well as methodologies for membrane testing. Additionally, various scholars have embarked on explorations using numerical simulation techniques. In recent years, research endeavors have included experimental examinations of simulated tunnel lining structures incorporating spray membranes. References [4-5] detail the collaborative efforts of the UK-based Aecom Corporation and Warwick University, which executed spray panel tests on composite shell linings within soft soil conditions, and conducted cyclic tensile and shear tests on the core for analytical purposes. References [6,7] present laboratory tests on sandwich beams, yielding load-deflection curves that substantiate a significant composite effect at the spray membrane interface. The University of Cambridge has engineered a compression bending test beam featuring a spray membrane layer, and has scrutinized the stress and strain variations of the specimens' sections throughout the loading process, initiating a preliminary investigation into the mechanical properties of the specimens [8]. Chinese scholars have also pursued research into the load-bearing mechanism, material characteristics, and structural design of the technology. Zhou Ping [9] employed experimental methodologies to dissect the stress characteristics of multi-layer lining structures under the influence of interlayer action. Previous research has indicated that each layer of multi-layer shotcrete exhibits a radial anti-slip effect, and when combined, they can constitute an integrated load-bearing structure. Jiang Yajun et al. [10] formulated numerical calculation models for double shell lining, composite shell lining, and single shell lining, grounded in the mechanical and interface parameters of the sprayed membrane derived from experimental measurements, and conducted an internal force analysis of the composite lining. Jiang Yajun et al. [11] explored the shear failure mechanism and mechanical properties of the interlayer interface within the double-sided bonded tunnel lining structure, procuring pertinent parameters based on the Mohr Coulomb constitutive model, which can be utilized as a foundation for assessing the failure of the contact surface within the double-sided bonded tunnel spray membrane lining. Deng Yisan [12] quantitatively assessed the integrity of structures with robust interlayer bonding, yet did not establish a mechanical correlation between the external load and the various composite layers.

This study employs laboratory experimentation to evaluate specimens featuring sprayed membrane at varying core angles. Through these tests, the adhesion force, internal friction angle, and shear stiffness of the sprayed membrane are determined. Subsequently, an ultimate tensile compressive shear strength envelope is constructed, serving as the threshold for the interface's resistance to slippage.

2 LABORATORY TEST

2.1 *Test Purpose*

In the elastic phase, the interface performance of the composite shell lining significantly impacts the overall stiffness and load-bearing capacity of the composite structure. Therefore, a quantitative analysis of the composite shell lining requires the precise measurement and comprehensive understanding of the mechanical properties of the interface.

The actual contact surface, comprising shotcrete and a sprayed membrane, is distinguished by its roughness and irregularity, presenting challenges for the mechanical performance analysis conducted on this surface. As a result, the paper posits the hypothesis of an interface layer.

The interface layer encompasses sprayed membrane and shotcrete that is in direct contact with it. Owing to the irregularity of the actual contact surface, contiguous media do not perpetuate a uniform deformation as a cohesive unit. Consequently, shear failure does not invariably transpire on the material's contact surface, but is more probable to emerge in the media layer encircling the contact surface, resulting in a shear dislocation layer proximate to the contact surface. The stress and deformation characteristics within this displacement layer are markedly distinct from those of the encompassing shotcrete. Hence, within the composite structure model of the waterproof single-layer lining, the sprayed waterproof material and the shotcrete at the interface are designated as a singular material interface layer, and it is presumed that its contact surface with the surrounding shotcrete is linear, as depicted in Figure 1.

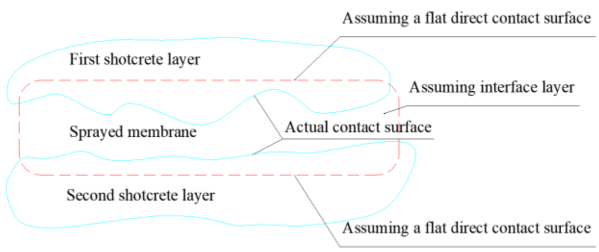

Figure 1. Schematic diagram of interface layer composition

The ultimate strength envelope of the interface layer, as delineated by the Mohr-Coulomb criterion, can be determined through shear compression and uniaxial tensile tests. By employing this envelope, the strength parameters of the interface layer can be obtained for simulation computations, thereby enabling precise determinations of interface failure occurrences within composite structures.

2.2 *Shear compression test on interface layer*

2.2.1 Test method

Given the intimate adherence of the contact surface between shotcrete and sprayed membrane to the irregularities of the tunnel excavation surface, the interface layer and the orientation of the ground load manifest varying inclinations. Consequently, the ultimate stress of the interface layer is ascertained through shear compression tests conducted on shotcrete core samples at differing interface inclinations. Standards such as ASTM 1583/C 1583M (Pull-off Method), EN ISO 4624 (utilizing a 50mm dolly), EN 1542, and JGJ372-2016 specify the fabrication of cylindrical specimens with a diameter of 50mm and a length of 100mm. However, the production of specimens with a diameter of 100mm and superior core quality is more feasible. Thus, a cylindrical specimen with a diameter of 100mm and a length of 200mm was crafted from a large plate test block.

A direct shear test requires repeated tests under several axial loads (typically three to five) to determine friction angle and cohesion. In contrast, an inclined/tilt shear test applies normal stress through the sample's inclination angle, allowing direct measurement of sliding angle in a single test—no complex loading apparatus or multiple test runs needed.The inclined shear test loads along a pre-existing discontinuity without artificially creating a flat base, thus more accurately capturing natural friction, block interlocking, and surface roughness effects. While direct shear testing is easier to perform, its imposed flat shear plane can lead to less realistic results.The tilt angle inherently includes both the material's internal friction and its surface roughness. Direct shear tests, by contrast, yield a linear envelope and often require multiple normal stress levels to estimate friction angle—but can't separately quantify roughness effects.A waterproof layer with varying inclination angles was interposed within the column, employing Sika lastic-245 as the waterproof material. The test specimen is depicted in Figure 2. A press machine was utilized to apply continuous loading to the specimen at a rate of 0.1Mpa/min until failure ensued.The test number, interface inclination angle and sprayed membrane thickness are shown in Table 1.

Figure 2. Test specimen before interface layer shear test

Table 1. Interface layer shear compressive test

No.	Specimen number	Interface inclination angle°	Interface finish (substrate roughness)	Membrane thickness mm
1	∠20°-1	20	As sprayed panel	2.3
2	∠20°-2		As sprayed panel	2.1
3	∠24°-1	24	As sprayed panel	2.2
4	∠25°-1	25	As sprayed panel	2.2
5	∠40°-1		As sprayed panel	2.1
6	∠40°-2	40	As sprayed panel	2.2
7	∠40°-3		As sprayed panel	2.1
8	∠45°-1		As sprayed panel	2.4
9	∠45°-2	45	As sprayed panel	2.2
10	∠45°-3		As sprayed panel	2.2
11	∠46°-1	46	As sprayed panel	2.3

2.2.2 *Result analysis*

Utilizing the experimental methodology delineated in the preceding section, the shear compression test was executed. The subsequent failure analysis is depicted in Figure 3, while the graphical representations of the test load and vertical displacement are presented in Figure 4.

(a)Destructive specimens after testing (b)The failure state of specimens at different angles

Figure 3. The failure state of the test specimen in the interface layer shear test

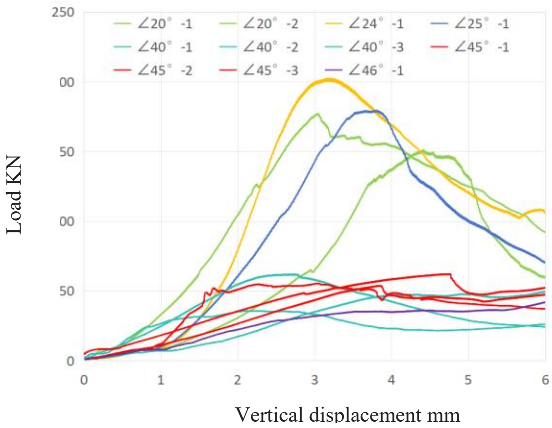

Figure 4. Load-displacement curve of interface layer shear test

As depicted in Figures 3 and 4, the shear compression failure of the interface layer is representative of a post-peak stress softening pattern. When the inclination angle of the interface layer is small, the normal stress at the interface significantly exceeds the tangential stress. Concurrently with the interface failure, the concrete substrate undergoes substantial compressive failure, and the peak value as well as the slope of the load displacement curve are notably high; Conversely, when the inclination angle of the interface layer is large, the disparity between the normal stress and tangential stress at the interface diminishes, and the failure is predominantly due to interface shear slip. The damage to the concrete substrate is minimal, and the peak value of the load displacement curve is also diminished, characterized by a relatively flat curve.

As depicted in Figure 4, the load displacement curve of the specimen serves as a comprehensive representation of the failure of the interface layer and the degradation of the concrete substrate, exhibiting no discernible linear segment. Consequently, this investigation employs the initial significant slope alteration point on the curve to compute the normal and tangential shear stresses of the interface layer, designating it as the inception of interface layer failure. The outcomes are delineated in Table 2.

Table 2. Results of interface layer shear test

Specimen number	Interface inclination angle°	Load kN	vertical displacement mm	Normal stress Mpa	shearing stress Mpa
∠20°-1	20	168.2	2.9	18.91	6.88
∠20°-2		128.2	3.7	14.41	5.24
∠24°-1	24	186.0	2.8	19.76	8.79
∠25°-1	25	173.7	3.5	18.16	8.47
∠40°-1		44.6	3.9	3.33	2.79
∠40°-2	40	36.2	2.1	2.70	2.26
∠40°-3		57.8	2.2	4.31	3.62
∠45°-1		62.0	4.7	3.94	3.94
∠45°-2	45	50.1	1.7	3.18	3.18
∠45°-3		53.4	3.8	3.39	3.39
∠46°-1	46	28.8	2.6	1.76	1.83

Upon linearly correlating the normal stress and shear stress of the interface layer within the stress domain, the Mohr-Coulomb shear compression strength envelope for the interface layer is derived, as depicted in Figure 5. From the fitting line equation y=0.3106x+1.9355 presented in the figure, the shear strength parameters of the interface layer are determined to be: cohesion of 1.9355 MPa, and an internal friction angle of arctan(0.3106), which equates to 17.3 degrees.

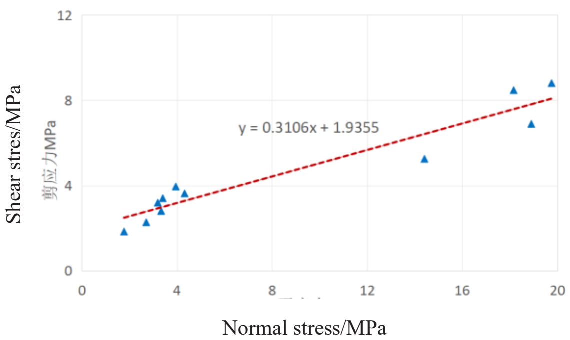

Figure 5. Envelope line of shear test strength of interface layer

2.3 *Uniaxial tensile test on interface layer*

2.3.*1 Test method*

In order to enhance the envelope of the interface layer within the tensile quadrant of the stress space, axial tensile tests were executed to ascertain its tensile characteristics. The experimental procedure also encompassed the fabrication of cylindrical specimens, each with a diameter of 100mm and a length of 200mm, derived from extensive plate test blocks. The composition of the specimens was identical to that utilized in the shear compression test.Due to the difficulty of coring at various inclined angles—particularly those less than 45 degrees—this tensile test uses sprayed membrane that is laid horizontally. The specimen is shown in Figure 6. A tensile machine was employed to apply a continuous load at a rate of 0.1 Mpa/min until the specimen succumbed to failure, with the locus of failure being significant at the interface layer.

Figure 6. Interface layer uniaxial tensile specimen

2.3.2 Result analysis

The specimen's predominant mode of failure is characterized by interfacial adhesion failure, specifically the detachment of the sprayed membrane from the mortar specimens at the interface subsequent to tensile stress application. The tensile test was executed in accordance with the methodology delineated in the preceding section. The maximum stress attained during the tensile process represents the peeling strength of the adhesive material, the test outcomes detailed in Table 3.

Table 3. Results of axial tensile test on the interface layer

Specimen number	ZL-1	ZL-2	ZL-3	ZL-4	ZL-5	ZL-6	ZL-7	ZL-8	ZL-9	ZL-10
Loa/kN	4.79	2.12	4.79	3.53	3.14	10.28	8.63	7.3	10.36	11.54
Axial tensile stress/Mpa	0.61	0.27	0.61	0.45	0.40	1.31	1.10	0.93	1.32	1.47

Throughout the stretching procedure, the initial phase exhibits a relatively slow rate of change in stress values, succeeded by a swift escalation of stress within a matter of seconds. Upon achieving bond strength, the waterproof membrane detaches from the mortar specimen in an almost instantaneous manner. In certain specimens, subsequent to the stress value attaining the bond strength, the stress diminishes incrementally until the membrane separates from the mortar block, signifying a gradual failure of the interface during the stretching process. For specimens characterized by immediate detachment of the membrane, the membrane completely separates from the mortar block, preserving its integrity post-separation of the bond surface. For specimens experiencing a gradual failure, both the interface separation and the destruction of the waterproof membrane transpire concurrently,the post-test failure analysis is depicted in Figure 7,

Figure 7. The failure state of the interface layer

Upon examining the outcomes of the axial tensile test, a tensile stress circle is delineated within the stress space. This tensile stress circle is subsequently linked to the shear compression envelope via an involute curve, culminating in the formation of the comprehensive tensile shear compression envelope, as depicted in Figure 8. The involute methodology is illustrated in Figure 9.

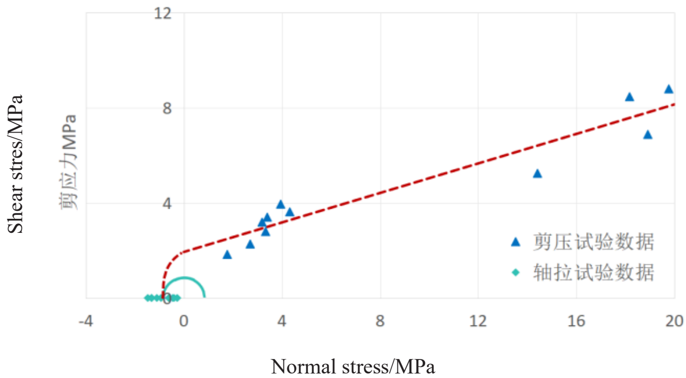

Figure 8. Envelope line of tensile, shear and compression test strength at the interface layer

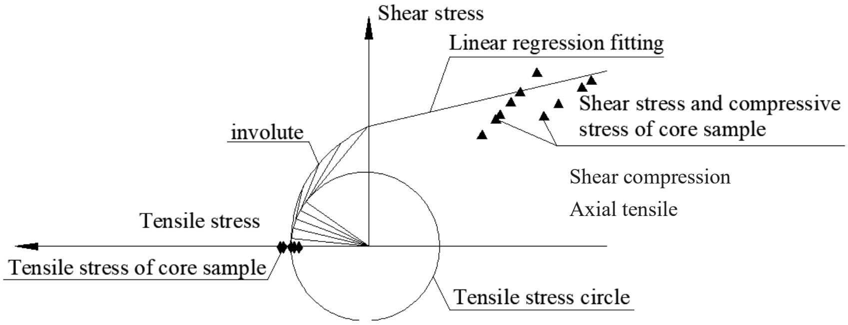

Figure 9. Illustration of the drawing of a gradual line

3 CONCLUSIONS

This study undertakes a comprehensive examination of the mechanical characteristics of the interface of a composite lining with an applied sprayed waterproof layer, employing laboratory-based testing methodologies. The investigation encompasses an interface layer shear compression test and a uniaxial tensile test, with the objective of ascertaining the interface layer's ultimate strength envelope in accordance with the Mohr Coulomb criterion.

(1) The shear compression test was executed on core samples of sprayed concrete at varying interface angles. The outcomes indicated that the shear compression failure of the interface layer exhibited a characteristic post-peak stress softening behavior, with the failure modality being influenced by the interface angle. The Mohr Coulomb shear compression strength envelope of the interface layer was derived via linear regression, and the shear strength parameters of the interface layer were obtained.

(2) The uniaxial tensile test quantified the tensile characteristics of the interfacial layer, revealing that the effective failure mode of the specimens was interfacial bonding failure. The standard bonding strength value can be considered as 0.5 MPa. Utilizing the outcomes of the axial tensile test, a tensile stress circle was delineated and integrated with the shear compression envelope to establish a comprehensive tensile shear compression envelope.

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