Study on the mechanical characteristics of rock-concrete Brazilian disc based on DEM

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ABSTRACT: The rock-concrete interface is usually considered the weakest structural zone in tunnel lining structures. To study the tensile failure of the rock-concrete interface, the Brazilian splitting tests were carried out on sandstone-concrete Brazilian discs using the digital image correlation (DIC) system. The laboratory tensile strength and failure process are consistent with numerical simulation. Then, the tensile behavior of the interface with different roughness was simulated using MatDEM software. Results show that the tensile strength of rock-concrete disc is insensitive to the sawtooth number. The tensile strength increases with increasing sawtooth angle due to increasing total contact area and interlocking effect. When the sawtooth angle is more than the critical value, the tensile strength increases rapidly due to the formation of the breaking sawtooth.

Keywords: Rock-concrete interface, Brazilian splitting test, Interface tensile failure, Interfacial roughness, MatDEM.

1 INTRODUCTION

The roughness of the rock surface resulting from blasting significantly impacts the strength of concrete-rock composite structures. The structure is widely used in tunnel lining (Tang et al. 2016), dam foundation (Milovanovic 1972 and Krounis et al. 2016), and other scenes. There is an increasing need to investigate the failure mechanism and process of this structure. Recently, various researchers have studied the shear strength of concrete-rock interfaces with different roughness and numbers of teeth. Saiang et al. (2005) concluded that the peak shear stress at the interface of concrete-rock composite was composed of bond strength and friction. However, most of concrete-rock interfaces were damaged by tensile force, especially under the influence of blasting during construction. Brazilian splitting test is a common method to assess the tensile of concrete-rock interfaces. Results from this test have demonstrated that the tensile strength is correlated with the angle and shape of the interface. As the angle of the interface increases or its shape changes, distinct failure modes can manifest in the Brazilian disk (Chang et al. 2018 and Qiu et al. 2020).

In this paper, the digital image correlation (DIC) is used as the reference for DEM calibration. Subsequently, a large number of numerical simulations are conducted to examine the tensile strength and failure mechanism of the concrete-rock interface under various tooth numbers and angles.

2 EXPERIMENTAL MATERIALS AND METHODS

2.1 Specimen preparation

In order to study the failure properties of rock-concrete interface, sandstone and C25 concrete are selected in this study and their mechanical property is shown in Table 1.

Table 1. The mechanical properties of sandstone and concrete.

Material	σ_c [MPa]	σ_t [MPa]	E [GPa]	ρ [kg·m^{-3}]
rock	30.5	2.1	2.8	2272
concrete	26.0	/	1.5	2280

σ_c is the uniaxial compression strength; σ_t is the direct tensile strength; E is the elastic modulus; ρ is the density.

2.2 Experimental equipment

The tests are conducted using the WDW-600C universal electronic testing machine with a loading rate of 0.005 kN/s. The failure process is observed using the DIC strain measurement system, which comprises a computer, lighting system, and camera system. The camera system has a maximum pixel count and frame rate of 1.6×10^7 pixels and 100 fps, respectively. Moreover, the system offers a strain measurement accuracy of 0.002% and a range of 0.005~2000%.

3 TENSILE STRENGTH AND FAILURE PROCESS OF BRAZILIAN DISC

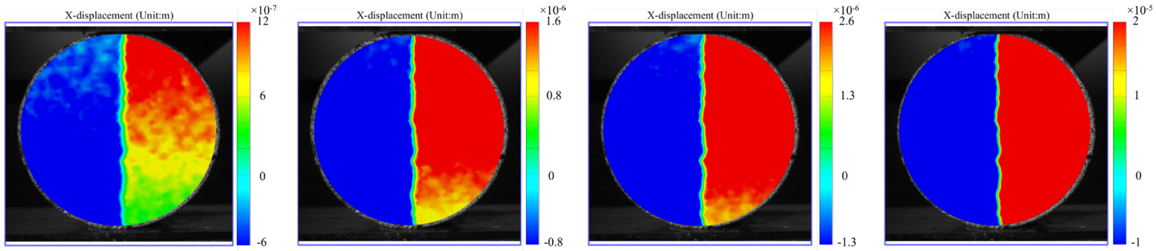
Through three Brazilian splitting tests, the tensile strength is in a range of 0.28~0.46 MPa with an average value of 0.36 MPa. The failure evolution of Brazilian splitting disc was captured using the DIC system. Figure 1 illustrates the X-displacement evolution process. At 5 s before failure, the concrete (right part) has remarkable displacement at the upper right side in the x direction. The X-displacement of the rock (left part) is uniform. The behavior is attributed to that the elastic modulus of the concrete is smaller than that of the rock, making the concrete more prone to deformation and ultimately leading to failure at the rock-concrete interface. Then, the lower right side also starts to displace from 3 s to 1 s before failure. In this interval, the interfacial crack propagation continues. Ultimately, the interfacial cracks propagate throughout the entire disk, as seen in Figure 1(d).

4 NUMERICAL SIMULATION WITH DIFFERENT TOOTH ANGLES AND NUMBERS

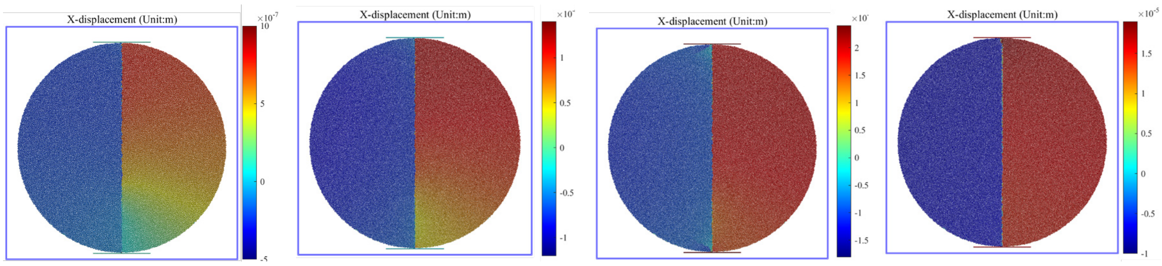
4.1 Numerical model

The MatDEM software based on the DEM is adopted to establish the numerical model. The mechanical behaviors of particles are simulated by linear elastic model (Xue et al. 2021). Figure 2 illustrates a two-dimensional numerical model of the Brazilian disc with a flat interface. The diameter of the disc is 50 mm, consistent with the laboratory disc in section 2. The model consists of 50,969 particles with a mean radius of 0.1 mm, and particle radii ranging from 0.084 mm to 0.120 mm.

Figure 2 shows the use of sandstone, concrete and interface materials in a two-dimensional numerical model with a flat interface. The micro-parameters of interface are calibrated using Brazilian splitting test. Figure 1 and 3 show the comparison between the laboratory and numerical failure process and stress-displacement curves, indicating good agreement. The micro-parameters obtained from calibration are used for further simulation of rock-concrete interface properties. Table 2 present the micro-parameters of sandstone, concrete, and interface. The load is applied by upper and lower platens composed of rigid particles.



(a) 5 s before failure (DIC) (b) 3 s before failure (DIC) (c) 1 s before failure (DIC) (d) failure (DIC)



(e) 5 s before failure (NS) (f) 3 s before failure (NS) (g) 3 s before failure (NS) (h) failure (NS)

Figure 1. Failure process of splitting specimens in Numerical Simulation (NS) and DIC (Sandstone on the left and concrete on the right).

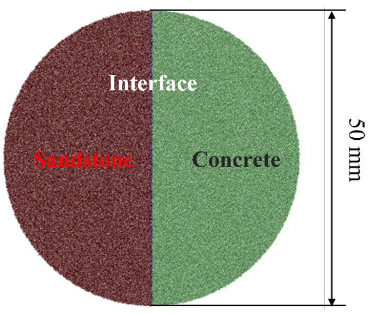


Figure 2. Numerical model of Brazilian splitting specimens.

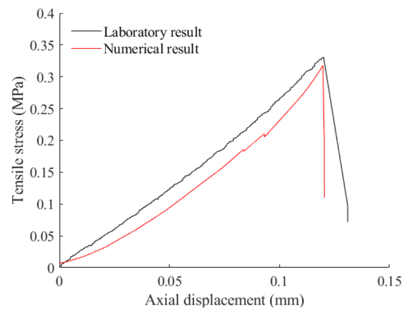


Figure 3. Comparison of laboratory and numerical results.

Table 2. Micro-parameters of sandstone, concrete and interface.

		Sandstone	Concrete	Interface
Normal stiffness *kn*	[MN/m]	6.03	4.55	0.34
Shear stiffness *ks*	[MN/m]	2.15	1.21	0.16
Breaking displacement *xb*	[m]	3.65×10^{-7}	9.76×10^{-8}	9.66×10^{-8}
Friction coefficient μ	[-]	0.15	0.18	0.12
Shear resistance F_{s0}	[N]	9.23	8.47	0.02

4.2 Simulation plan

In practical engineering, the interface between surrounding rock and shotcrete is rough rather than flat. It is necessary to study the failure characteristics of the interface with different roughness. Figure 4 shows the numerical model with different interface angles and numbers. Bista et al. (2020) counted the distribution of sawtooth at different angles. In this study, the interface is determined by the angle and number of sawtooth. Most sawtooth angle concentrated between 10 ~ 50 ° (Ma & Huang 2018). The adhesive properties of interface are determined by two factors, i.e., mechanical interaction and adhesive force (Zhu et al. 2020). To study the effect of roughness on interface tensile behaviors, simulations are performed with 7 tooth angles (10 °, 15 °, 20 °, 25 °, 30 °, 35 ° and 40 °) and 6 tooth numbers (3, 6, 9, 12, 15 and 18).

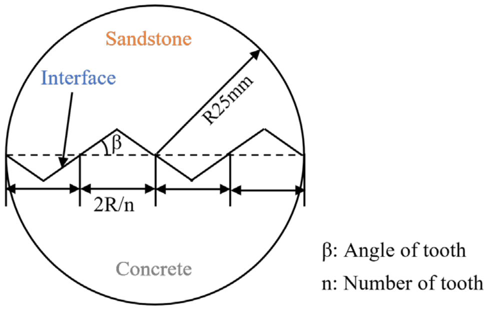


Figure 4. Numerical model with different interface angle and number.

4.3 Results and discussion

4.3.1 Effect of sawtooth number on the tensile strength of rock-concrete disc

Figure 5 shows the relationship between the sawtooth number and tensile strength for various sawtooth angles. At smaller sawtooth angles (10° and 15°), the tensile strength shows little variation with the sawtooth number, fluctuating around a specific value. The fluctuation of tensile strength increases at sawtooth angles of 20° and 25°, and then decreases at sawtooth angles of 30° and 35°. The results suggest that increasing the sawtooth number does not improve the tension resistance, and the sawtooth angle plays a crucial role in avoiding tensile failure. Therefore, it is necessary to investigate further the impact of the sawtooth angle on the tensile failure of the rock-concrete Brazilian disc.

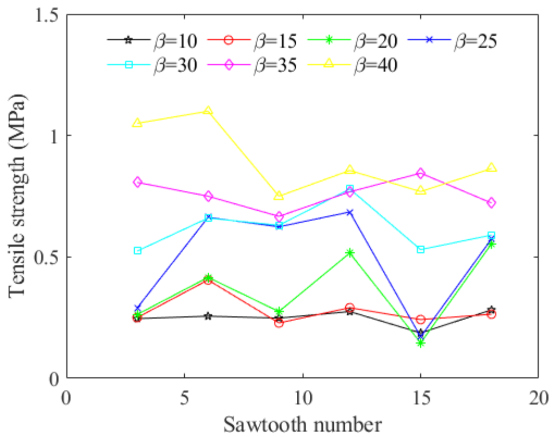
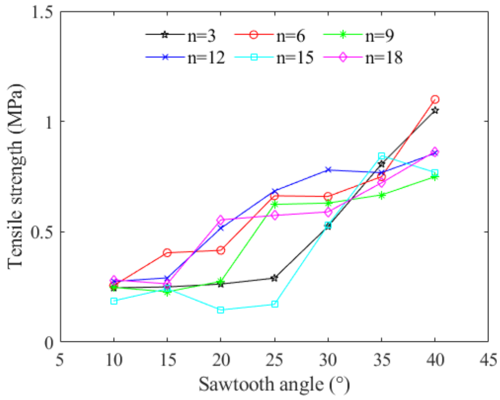


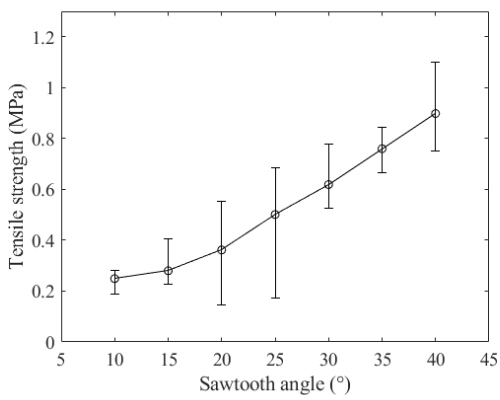
Figure 5. Tensile strengths versus the sawtooth number.

4.3.2 Effect of sawtooth angle on the interfacial failure characteristics

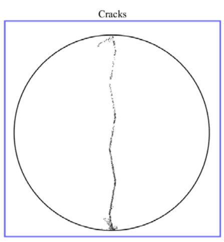
Figure 6 shows the tensile strengths of rock-concrete disc and failure patterns versus different sawtooth angle for different sawtooth number. Result shows that, with increasing sawtooth angle, the tensile increases for all sawtooth number. This is due to the increasing total contact area between the rock and concrete with increasing sawtooth angle, which determines the adhesive force. Larger sawtooth angle stands for higher sawtooth roughness. In general, the tensile strength will increase if the interfacial roughness is larger, which is confirmed in laboratory results (Zhu et al. 2020). However, the relationship is not linear. When the sawtooth number equals to 3, the tensile strength increases slowly until sawtooth angle is 25°. Then the tensile strength increases sharply after sawtooth angle exceeds 25°. This suggests the existence of a critical sawtooth angle that determines whether the tensile strength increase rapidly. For different sawtooth numbers, the critical sawtooth angle is also different. Two critical sawtooth angles (20° and 25°) are observed in this simulation, and the fluctuation of different sawtooth numbers is more significant at these angles, as shown in Figure 6(b).



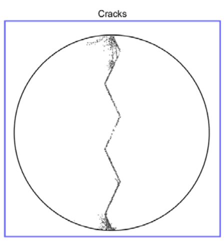
(a) Tensile strength versus sawtooth angle.



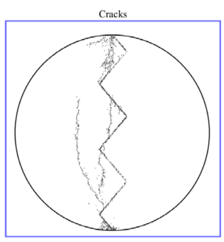
(b) Mean tensile strength and limit of different sawtooth numbers.



(c) n=6 and β=10°.



(d) n=6 and β=25°.



(e) n=6 and β=40°.

Figure 6. Tensile strength and failure patterns versus sawtooth angle.

The rise of sawtooth angle not only increases the total contact area, but also increases interlocking effect, which will enhance the tension resistance. As shown in Figure 6(c), (d) and (e), when the sawtooth number equals to 6, the cracks produce mainly along the interface at small sawtooth angle (β=10°). However, at critical sawtooth angle of 25°, the breaking sawtooth can be found at the upper part of the Brazilian disc. This is due to the mechanical interaction of the sawtooth, which is also a part of the tension resistance. It proves that the rapid rise of tensile strength mostly attributes to the formation of breaking sawtooth. At larger sawtooth angle (β=40°), more sawteeth are cutting off under the tension stress. With increasing sawtooth angle, the proportion of mechanical action is greater, resulting in more cracks and breaking sawteeth. These observations indicate that with the increasing sawtooth angle, the interlocking effect can be effectively exerted via the mechanical interaction between the rock and concrete. After the sawtooth angle exceed the critical value, the rapid rise of the tensile strength is partly due to the formation of breaking sawtooth.

5 CONCLUSION

By Brazilian splitting tests using DIC and DEM simulation, main conclusions are listed as follows:

1. The Brazilian splitting tests were conducted to study the failure process of rock-concrete interface by DIC system. According to the failure process, the laboratory and numerical results are consistent and the DEM calibration is well performed.
2. The tensile strength of rock-concrete disc is insensitive to the sawtooth number but the fluctuation around the mean value is different when the sawtooth angle is different.
3. With increasing sawtooth angle, the tensile strength increases due to the increasing total contact area and interlocking effect. When the sawtooth angle is more than the critical value, the tensile strength increases rapidly because of the formation of breaking sawtooth.

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