Mechanical Experiments on the Interaction between 3D Cracks in Simulated Rock Materials under Uniaxial Load

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***Abstract* — In order to understand the rules of rock cracks expanding process, a similar material to rock made of resin was studied. A series of uniaxial compressive tests of samples with 3D vertical double cracks were performed in the laboratory. The test was to investigate the mechanisms of crack propagation and coalescence. The result indicated that the interactions between 3D cracks mainly affect crack's appearance, growth and extension in two ways. First, promote each other or restrain each other: the mechanism of crack interaction depends mainly on the relative location of cracks in the process of extension and evolution. Second, a change of the relative positions of the 3D crack makes the rock bridge more complex to coalesce, and numerous different test results were obtained to verify this. Our work here is close to engineering geological conditions and it has important meaning for geotechnical engineering.**

Keywords - uniaxial compressive; vertical cracks; interaction; the coalescence of bridge.

I. INTRODUCTION

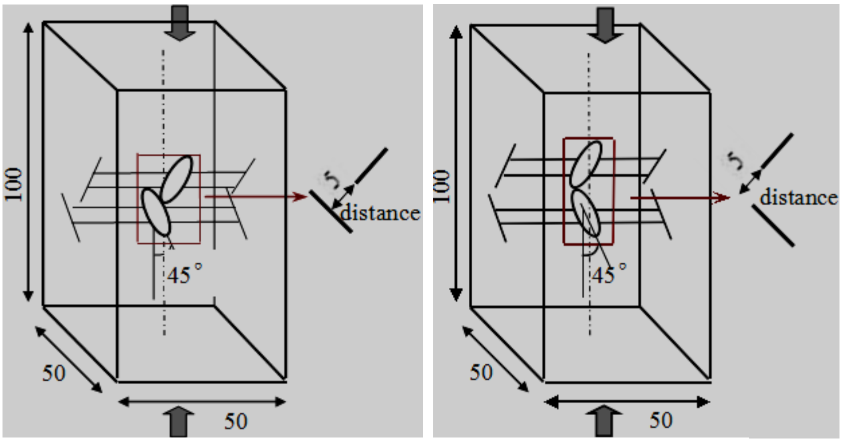
The rock usually contains many cracks. The interaction of such cracks and the mechanisms of crack coalescence is an important topic in rock fractured mechanics area. The rock damage is one of the main causes of its instability. Whether the sheared partial destruction or the overall destruction, the root reason of damage is that the rock contains a variety of cracks with different scales and relative positions. Rock dynamic disasters, such as Rock blasting, mined earthquake and tectonic earthquake , et, are essentially due to a instability process of the rock fracture propagation and evolution, but the mechanism of these dynamic phenomena is not very clear currently. So the study of its generation mechanism and its accurate prediction and forecasting has become a major topic of rock fracture mechanics in the 21st century (ROBET A&EINSTEIN H1998;Weishen Zhu et al1998; Wancheng Zhu &Tang Chun-an 2000 and WONG R H C et al.2001).

However, due to the opaqueness of the rock material, the procedure of 3D cracks' extension and evolution is difficult to be directly observed in the rock after loading. In recent years, experimental research in this area has made preliminary results and they described the fracture features of a single crack or many cracks (ADAMS M &SINES G 1978, HORII H&NEMAT-NASSER S 1985, Chunkai Teng et al 1987and DYSKIN A V et al 1994).Some scholars have carried out a number of 3D crack's growth tests or done the preliminary simulation .for example, the work reported in the world(, WONG R H C&CHAU K T1998, LISY et al 1998, DYSKIN A V et al2003, Dongmei Liu et al 2006, Shucai Li (via CT scan) et al 2007, Yanshuang Guo 2008 and Weishen Zhu& Jinwei Fu2013). They used a variety of rocks, ceramics, glass, resin and plaster to produce samples pre-containing 3D cracks and studied the influence of different crack depth and direction on the crack extension form and then got some preliminary results. In experimental studies, the joint position used in previous study is just ordinary spatial location, for example, the test (Mingli Huang 2007)used parallel cracks. This is far less than to explain the interaction between the joints with different relative positions under the complex geological conditions.

In this paper a series of uniaxial compressive tests on the new resin material samples with 3D vertical double cracks in similar to the rock have been done in laboratory to study the mechanisms of crack propagation and coalescence and the influence of the spatial domain, it also discusses the effect of the relative position of joints to the crack propagation in the procedure of crack growth. The biggest benefit of this study is that its test condition is much closer to the engineering conditions, so it has larger significance to promote the experimental research, the theoretical analysis and its application in geological engineering field in the future.

II. EXPERIMENTAL DESIGN

The main purpose of this experiment is to explore the influencing factors and the mechanisms of crack propagation and coalescence between the 3D vertical double cracks under uniaxial loading propagation; to elucidate the differences crack coalescence mechanism; to explore the effect of the relative position to the crack propagation; to analysis the stress characteristics and the effect factors in the procedure of the crack propagation and the coalescence of the rock bridge. For these purposes, three groups of models are designed and the model parameters are shown in figure 1.



Case 1: on the vertical   Case 2: from the vertical.

Figure 1. the design of case.

III. MATERIAL SELECTED

This study uses new brittle and transparent materials to make samples according to the research (Weishen Zhu & Jinwei Fu.2013). Resin material is made of resin, curing agents and accelerators, et al by a certain percentage. Temperature and the ratio are the biggest two important Influence factors to the Mechanics property of resin material. Resin material used to simulate mult-fractured rock is close to the brittle rock and can used to stimulate a large number of intermittent joints in a certain pattern. So through experiment, the new resin material's mechanical parameters 、Brazilian split curves and stress-strain curves under certain temperature conditions can be get, which is shown in Table 1 and Figure 2.

TABLE 1. THE PARAMETERS OF NEW RESIN MATERIAL MECHANICAL

Parameter	Value	Parameter	Value
Density/ $g \cdot cm^{-3}$	2.6	Brittleness[1]	6.2
Modulus of elasticity,E(GPa)	6.5	Cohesion	21.8
Compressive strength, σ_{bc} (MPa)	108.8	Angle of internal friction，φ	46.3°
Tensile strength，R_m （MPa）	17.5		

[1] Brittleness: Compressive strength is divided by tensile strength

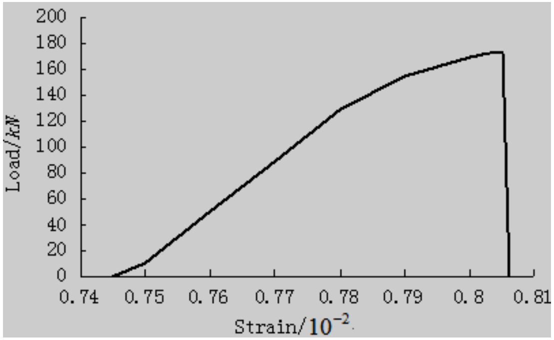


Figure2. The stress-strain under uniaxial load

The paper takes the embedded method with a thin mica in order to simulate a closed joint inside. Comparing with other materials, mica's stiffness is low, and it won't bound the sample to deformation, so that it's more convenient to fix the cracks' position and let them closer to the cracks in the rock. To reduce edge effects and to make result symmetry, this paper uses the $14 \times 20mm$ mica as joint piece.

IV. 3D SAMPLE PREPARATION

The dimension of sample is $50 \times 50 \times 107mm$. It is made of five Perspex sheets, bonded as a sealed container by organic insulating silicon grease. The mold's transparency is so good that we can directly observe the curing. The hole is laid ahead in a different location, then 3D joints are preset by thin and the vacuum resin material is casted in the mold. After the resin solidifying we can removal the mold, so we can get the $50 \times 50 \times 100mm$ 3D joint sample inside, as shown in Figure3.

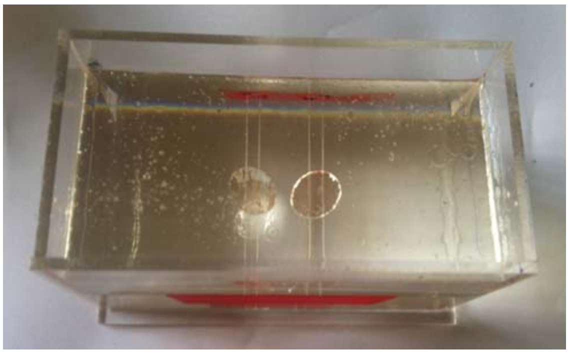


Figure 3 . the pouring process of Sample.

A. Sample loading

The uniaxial loading test uses the TJH-4B-type machine. Load and displacement are all handled by a data receiving apparatus connected to the computer connected .The procedure of crack growth will be recorded with the SONY DSC-T70 digital camera and the speed is 5 / s. In the initial loading, the loading rate is controlled to 1.5 kN/s. When the crack appears, half the loading rate (i.e. 0.8kN/s) to let the crack propagation process to be easier observed. When doing the test, the sample loading is carried out in the refrigeration warehouse to avoid too much temperature fluctuation and the using time from loading to destruction is shortened as far as possible to not more than 15min to ensure the temperature rise to not higher than -30 ℃ at the end of the test. If the temperature drops too quickly and lead to the plastic deformation finally, it would be excluded during the analysis and no adoption.

B. Analysis of the 3D double crack growth

This paper carried a large of oval double-crack experiment, despite the different arrangement of the original crack will result in crack propagation and coalescence various forms, but there are some common in the propagation and coalescence between the 3D vertical double cracks. It is completely different from the propagation and coalescence of the 3D single crack, 3D parallel cracks and 2D crack. The picture in figure 4 is a typical 3D crack propagation process and detailed character by Adams with theoretical analysis.

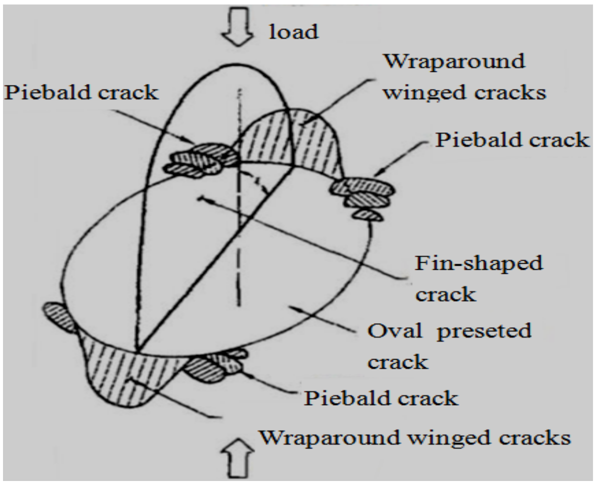


Figure 4 Adams's forecasting model.

C. Propagation of double crack on the vertical under uniaxial loading

For a better effect of shooting, a set of identical samples will be produced and loaded to a rupture state respectively, then pictures are taken. Through contrast, accidental results can be removed. The compressive strength is 81.3MPa, and the paper summarizes the phenomena and laws. The top of the crack from top to bottom is labeled 1,2,3,4,to the description conveniently. The crack propagation experiences four stages ,as it follows:

(1) In initial compacted stage, stress is from 0 to 27% of the peak intensity.

(2) In the stage of elastic deformation, the stress is from 27% to 52.8% of the peak intensity. While the stress is 33.5% of the peak intensity, a winged crack appears in 1 of the preseted crack; with that, a winged crack appears in 4 of the preseted crack and they keep growing in same pace. However, no winged crack appears in NO.2 and NO.3, until the crack extends to a certain size. At this time, the crack in NO.1 and NO.4 develop to a wing-shaped crack and a piebald crack, and they continue to develop.

(3)In the stage of crack propagation, the stress is from 52.8% to 74% of the peak intensity. When continuing loading, the winged crack appear suddenly in NO.2 and NO.3 and they are all growing. Keeping on loading, the wraparound wing cracks in 1 and 4 propagate along the edges of the preseted crack to the opposite direction of it and the preseted crack in 1 and 4 become larger petal-shaped cracks.

(4)In the accelerating expansion stage of crack, the stress is from 74% of peak intensity to damage. The front of petal-shaped crack continues to extend by in a curl vertical-type. Until a moment, the bearing capacity of sample begins to decrease. The vertical crack in 1、3、4 has developed rapidly and eventually form a macroscopic fracture plane and lead to the sample’s split. as shown in figure5.

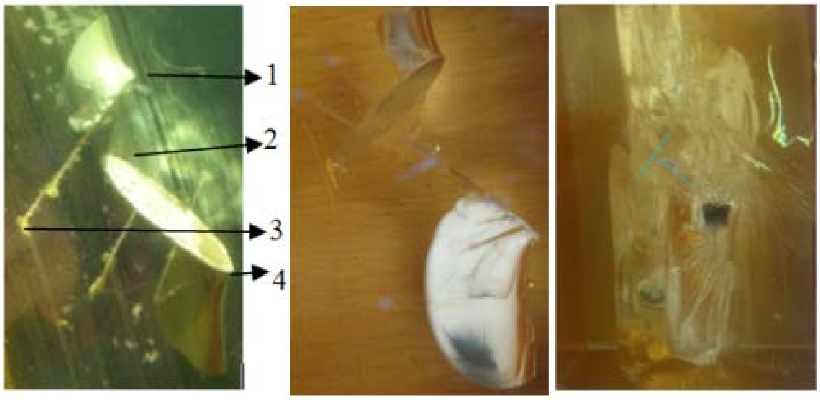


Figure 5. the propagation process of crack on the vertical.

D. Propagation of double crack from the vertical under uniaxial loading

The size of samples is identical with the previous section, but the centroid of the two cracks is on the same axis. They are perpendicular to each other and there are some offsets between them. The compressive strength is 75.9 MP_a . For description convenience, the cracks from top to bottom are labeled 1,2,3,4. The crack propagation also experiences four stages, as it follows:

(1) In initial compacted stage, stress is from 0 to 27% of the peak intensity.

(2) In the stage of elastic deformation and perforation, the stress is from 13.6% to 57.3% of the peak intensity. While the stress is 13.6% of the peak intensity, a winged crack appears in No.2 presented crack, with that, a winged crack appears at No.3 presented crack, and they keep growing in same pace. When the stress is 44.6% of the peak intensity, two crack are merged into a butterfly crack, then they change the original extension direction into towards the two sides respectively. But no winged crack appears at No.1 and No.4 presented crack, until the crack extends to a certain size.

(3)In the stage of crack propagation, the stress is from 57.3% to 77.3% of the peak intensity. When continuing loading, winged cracks suddenly appear at No.1 and No.4 presented crack and other cracks keep on growing. Going on loading, the butterfly crack propagates along the edges of the presented crack and to the opposite direction of it. The presented crack No.1 and No.4 become larger petal-shaped cracks.

(4)In the stage of crack accelerating expansion, the stress is from 74% of peak intensity to damage. The front of petal-shaped crack continues to extend with a curl vertical-type and until a moment, the bearing capacity of sample begins to decrease. The lateral presented crack at No.2 and No.3 develops rapidly, and eventually form a macroscopic fracture plane and lead to the sample’s laterally split, shown as figure6.

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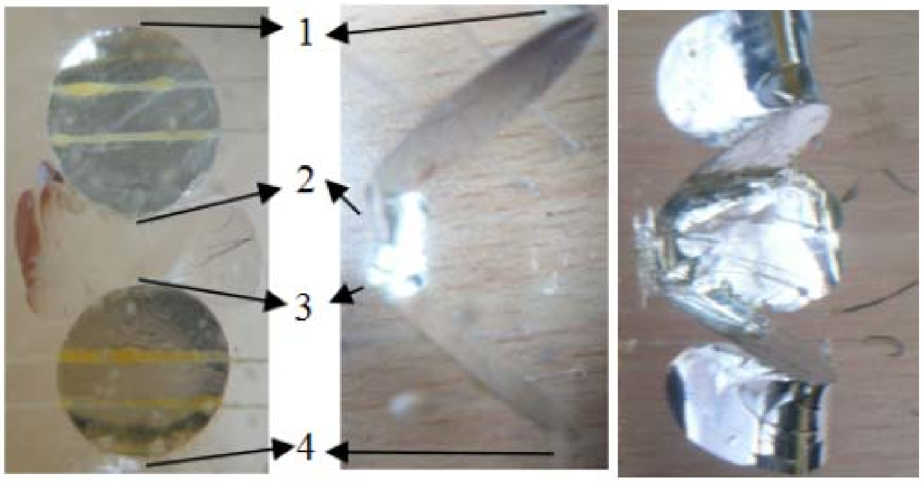

Figure 6. The propagation process of crack from the vertical

E. *Result and Discussion*

Compared with the previous studies in Figure 7 (Weishen Zhu& Jinwei Fu.2013),

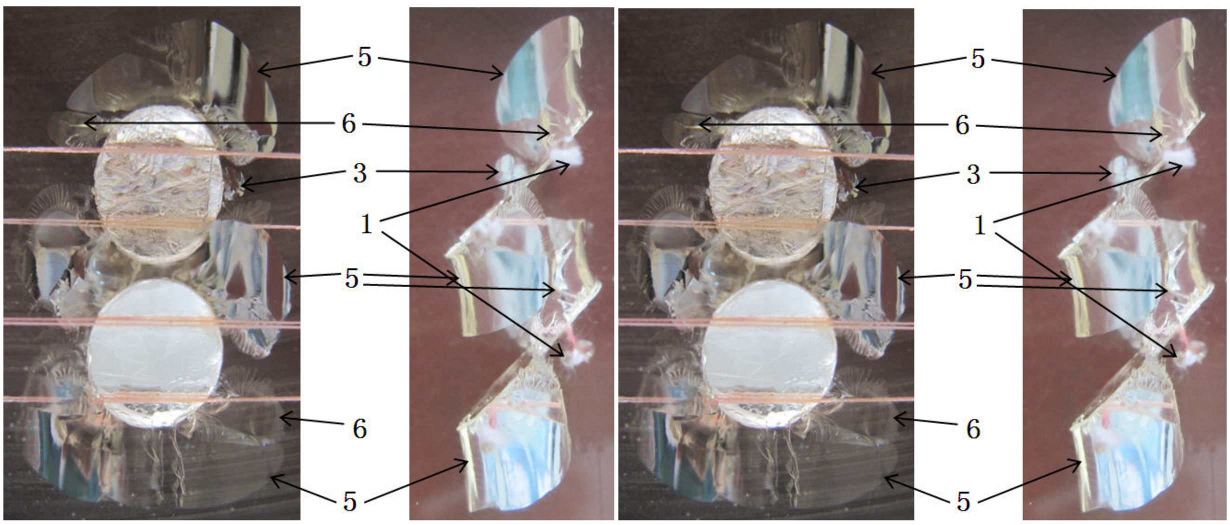

Figure 7. the test results in reference (Weishen Zhu & Jinwei Fu.2013).

From above figure, some initiation rule and fracture pattern is newly discovered in this experiment, such as bridge coalescence, crack inhibition phenomenon. Analysis on the test results are as follows:

(1) Due to the different 3D spatial distribution, a number of different phenomena appear when double cracks is compared with single crack and parallel cracks. Such as the initiation rule of secondary cracks, the fracture pattern of piebald crack, and the of coalescence et al.

(2) The compressive strength of the sample is decrease significantly due to the 3D double cracks inside. The compressive strength of the crack on the vertical is reduced to 85% of the original strength and the compressive strength of the crack from the vertical is reduced to 74.5% of the original strength. The interactions of double cracks is obvious: the crack on the vertical suppresses the development of secondary joint, the reduction of peak strength is small; the crack from the vertical promotes the development of secondary joint, the reduction of peak strength is big.

(3) The new type cracks are emerging in the crack from the vertical. The middle part of the cracks is completely

matched in coalescence. They form a butterfly-shaped crack and develop along each side, but not along the original direction.

(4)As to the compressive strength, the development of double cracks inside is not affected. The development of double cracks outside is severely affected.

(5) The coalescence of rock bridges is also been affected. Hardly any coalescence phenomenon emerges before splitting to the crack on the vertical, while the coalescence phenomenon emerges in the early stage of elasticity to the crack from the vertical, which accelerates the generation of fracture plane.

V. CONCLUSION

By the uniaxial compressive tests on the resin material samples with 3D vertical double cracks, this paper analyzes the mechanisms of 3D crack's propagation and coalescence and also discusses the interaction between the cracks. The conclusion is as follows:

(1) A new transparent resin material is used in the experiment. It's brittleness (the ratio of tensile and compressive strength) can be 1/6.6 at a low temperature. Its brittleness has been greatly improved and is more closer to the rocks with more stable performance, so the sample is easier to make. Its transparency is improves, so clearer photo can be taken. These provide a reliable basis for the authenticity of the experimental results.

(2)The sample containing 3D double cracks is produced to investigate the mechanism of crack propagation and coalescence and the interaction of double cracks, when it is under uniaxial pressure. The process of the sample's fracture can be divided into four stages. Its four stages of deformation is fully correspond to the rock's and it is found that the sample has a very significant characteristic of expansion which is similar to rock.

(3) This paper breaks through the conventional ideas of predecessors and explores the relationship of double cracks and finds many phenomenon that are undiscovered by predecessors. For example, the mechanisms of crack propagation and the phenomena in the second and third stages are never recorded by pictures both in domestic and abroad, but the phenomenon does appear in this paper with clear graphics and instructions. Also the fractured specimen test, it does never be found that the butterfly-shaped secondary cracks appear in the crack from the vertical ,because the promotion and the end of the cracks develop rapidly and the middle of the cracks are suppressed in the crack on the vertical by predecessors before in the test.

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