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Stress evolution and failure process of Brazilian disc under impact

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Abstract: To reveal stress distribution and crack propagation of Brazilian discs under impact loads, dynamic tests were conducted with SHPB (split Hopkinson pressure bar) device. Stress states of specimens were monitored with strain gauges on specimen surface and SHPB bars. The failure process of specimen was recorded by ultra speed camera FASTCAM SA1.1 (675 000 fps). Stress histories from strain gauges offer comprehensive information to evaluate the stress equilibrium of specimen in time and space. When a slowly rising load (with loading rates less than 1 200 N/s for *d* 50 mm bar) is applied, there is usually good stress equilibrium in specimen. The stress distribution after equilibrium is similar to its static counterpart. And the first crack initiates at the disc center and propagates along the load direction. But with the front of incident wave becoming steep, it is hard for specimens to get to stress equilibrium. The first crack may appear anywhere on the specimen together with multiple randomly distributed secondary cracks. For a valid dynamic Brazil test with stress equilibrium, the specimen will break into two halves neatly. While for tests with stress disequilibrium, missing strap may be found when broken halves of specimens are put together. For those specimens broken up neatly at center but having missing wedges at the loading areas, it is usually subjected to local buckling from SHPB bars.

Key words: dynamic Brazil test; Brazilian disc; stress evolution; failure pattern

1 Introduction

Brazil test, or the diametrical compression test, is a well-known method to obtain the indirect tensile strength of BD (Brazilian disc) specimen statically. Since HERTZ brought up the theoretical expression describing the stress states of a circular disc under diametrical loads [1], the method has been greatly developed and widely used for various materials [2–4]. The easy preparation of specimen and simple test operation eventually make it an ISRM (International Society for Rock Mechanics) suggested method for determining static tensile strength of rock materials [5].

In recent years, the method has been further taken experimentally or numerically to investigate dynamic tensile strength of rocks [6–8]. But the dynamic response of BD specimens under impact is far more complicated than that under static loads [9]. When an elastic BD specimen is loaded diametrically with static forces, the stress states in specimen are determined and the stress equilibrium is achieved automatically. With the stress at disc center satisfying the Griffith criterion, the first crack initiates there [1, 10–11]. However, when dynamic loads are applied, the time effect of wave propagation and the inertia effect of specimen must be considered. The stress distribution and failure process of specimen become very complicated. It is difficult for specimen to reach stress equilibrium at time and space fields simultaneously. Premature failure can be observed at the loading areas in specimens [7]. Some attempt has been made to produce flattened BD specimen to avoid this problem [12]. But the preparation of fattened BD specimen is costly and needs high accuracy. In contrast, circular BD specimens are cheap and easy to prepare. So, the dynamic test with circular BD is very common in practice in spite of the controversy that the stress evolution of specimens under dynamic loads is totally different from that under static loads.

For specimens under dynamic loads, the stress distribution pattern is similar to its static counterpart only when the diametrical loads reach equilibrium. But for dynamic loads, the stress equilibrium can only be achieved transiently. Whether the first crack will initiate at the specimen center is hard to know. Even the first crack initiates at the specimen center, it is still difficult

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for it to spread diametrically because the stress wave velocity is larger than the crack propagation velocity. So, it is important to experimentally investigate the stress evolution and failure process of BD specimen under impact loads.

In this work, dynamic Brazil tests are conducted with the aid of SHPB (split Hopkinson pressure bar) device. Stress histories of specimen are captured to reveal their time and spatial characteristics. Ultra speed camera is used to record the failure process of specimen. Stress equilibrium of specimen is evaluated and failure patterns are discussed.

2 General response of Brazilian disc under static and dynamic loads

2.1 Brazilian disc under static loads

The stress solution for a disc under static diametrical load was first obtained by HERTZ in 1883, and then was refined some years later by HONDROS [1] to account for distribution loads over narrow strips of width on discs. With the solution, magnitudes and directions of principal stresses of specimen under static diametrical loads can be determined.

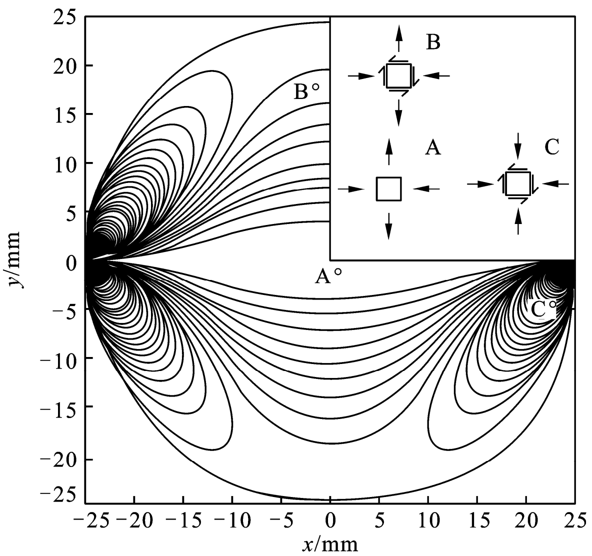

Fig. 1 Stress states and tensile stress contour of Brazilian disc under static load

As shown in Fig. 1, when an elastic circular disc is pressed diametrically along x direction, the stress states at points A, B, and C are determined and the stress contour at y direction can be mapped. At the disc center, the stresses satisfying the Griffith failure criterion, once the tensile stress reaches the tensile strength of specimen, the primary fracture would occur there and propagate along the load direction.

2.2 Brazilian disc under dynamic loads

When the disc is subjected to dynamic loads, stress wave would generate and it would spread, reflect and refract in the disc. There is no automatic stress equilibrium as that in the static case. The stress evolution and failure process of discs depend strongly on the dynamic load profiles and specimen sizes. Most of all, the stress equilibrium of discs under static loads is only in space field, but Brazilian disc under dynamic loads will experience not only the spatial non-uniformity but also the time non-uniformity. The complex stress states also make it difficult to predict crack propagation in specimens beforehand.

3 Experimental investigation of stress evolution in Brazilian disc under impact

3.1 Experimental design

As schematically presented in Fig. 2, the SHPB device was used for the tests. The special shape striker was used to produce slowly rising incident wave [13–15]. The short cylindrical specimen was sandwiched between the input and output bars. The bars were 2 m long and 50 mm thick. In the middle of bars, there were strain gauges to capture the stress histories.

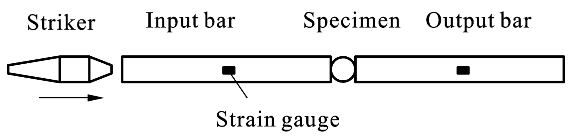

Fig. 2 Sketch of dynamic Brazil test with SHPB

In order to representatively capture the tensile stress states of the specimen, five strain gauges were mounted on the specimen surface with length perpendicular to the load direction, as shown in Fig. 3. The P_1 and P_2 represent the unbalanced dynamic loads applied on the specimen.

Siltstone rock, with good elasticity and homogeneity, was selected to prepare specimens with designed size of

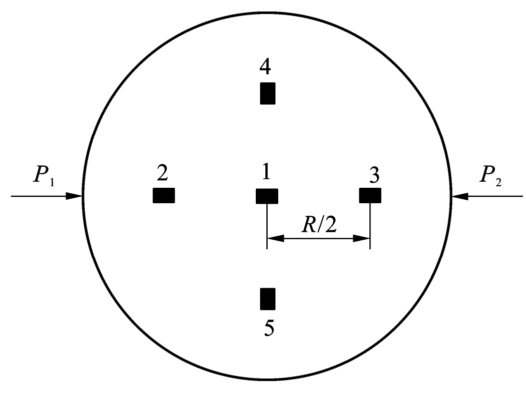

Fig. 3 Arrangement of strain gauges on specimen

d 50mm×25mm. Careful inspection has been made to ensure the specimen to have surface roughness less than 0.02 mm and end surface perpendicularity to the specimen axis less than 0.001 rad.

Besides strain gauges monitoring the dynamic stress signals, ultra-speed camera (FASTCAM SA1.1, 675 000 fps) was used to record the failure process of specimen photographically during tests.

3.2 Stress evolution of specimens

After careful calibration of the test system [16–17], specimens were placed and the striker was fired. Upon the striker impinging the input bar, the incident wave was generated and propagated along the input bar. At the interfaces of specimen and steel bars, waves were reflected and transmitted. The reflected wave together with the incident wave was captured by the strain gauge on the input bar, and the transmitted wave was captured by the strain gauge on the output bar. At the same time, five strain gauges on the specimen gave detailed stress information of specimen.

To get good stress equilibrium in specimen, low level dynamic loads were usually used. The load levels could be regulated by changing the air pressure driving the striker. With air pressure of 0.5 MPa, Specimen 1 with parameters in Table 1 was tested. The loading rate was about 1 000 N/s.

Table 1 Parameters of specimens in tests

Specimen No.	Diameter/ mm	Length/ mm	Density/ $(kg \cdot m^{-3})$	Longitudinal wave velocity/$(m \cdot s^{-1})$
1	49.20	24.76	2 481.26	3 438.89
2	49.14	24.62	2 505.32	3 517.14

Figure 4 shows the stress histories of Specimen 1 on its surface. The signal of strain Gauge 1 indicates that the stress at the specimen center increases the most quickly and the strain gauge is broken at 415 μs. The signals of Gauges 2 and 3 almost coincide with each other until their break at 452 μs, which means that there is good stress equilibrium in specimen. This also indicates that the specimen splits up diametrically. The stresses at the points of strain Gauges 4 and 5 coincide with each other before 452 μs. This again reveals that the stress symmetry and force balance in specimen are very nice.

The stress equilibrium can also be verified by the stress histories recorded from the input and output bars. As can be seen from Fig. 5, the sum of the incident stress and reflected stress coincides with the transmitted stress rather well before the rupture of specimen. This ensures that the dynamic Brazil test results are correct. The final tensile strength of Specimen 1 is calculated as 23 MPa.

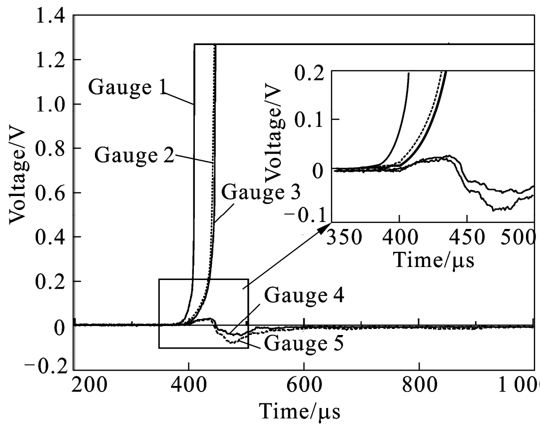

Fig.4 Signals captured by strain gauges on Specimen 1

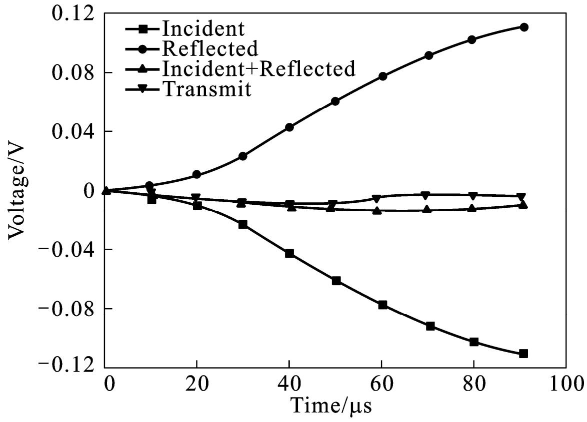

Fig. 5 Stress histories on SHPB bars in test of Specimen 1

In some tests, strong impacts may be needed to get tensile strength of specimen at high strain rates. In this case, the wave front of the incident wave becomes very steep. This makes it hard for the specimen to get stress equilibrium before its failure. For example, Specimen 2 with parameters in Table 1 was tested under impact with striker driven by air pressure of 0.8 MPa. The loading rate was about 1800 N/s. The stress histories on the specimen are presented in Fig. 6.

At this time, the first crack initiation also happened at the position of strain Gauge 1 and the time was 440 μs, but the strain gauge did not break apart immediately. Almost at the same time, new crack appeared at the position of strain Gauge 2. Once micro cracks came into form, stresses at these points were released. At 460 μs, strain Gauge 3 was pulled apart. Till 470 μs, strain Gauge 2 was pulled apart finally. Strain Gauges 2 and 3 did not break up at the same time. This can be explained with the fact that multiple cracks have come into being in the specimen, but they did not spread with the same path. Stresses of strain Gauges 2 and 3 did not coincide with each other. This indicates that there was no stress equilibrium in the specimen. The stresses from the input and output bars also show the stress disequilibrium in specimen, as shown in Fig. 7. The

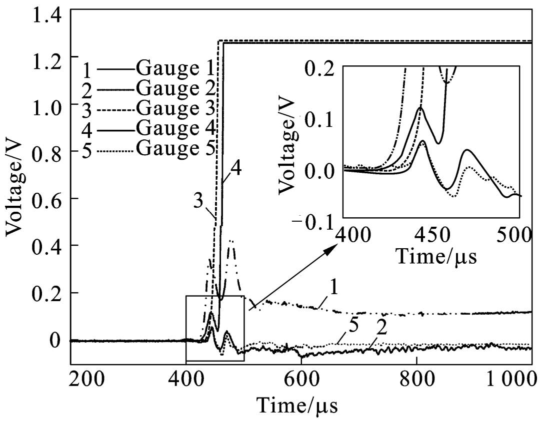

Fig. 6 Signals from strain gauges on Specimen 2

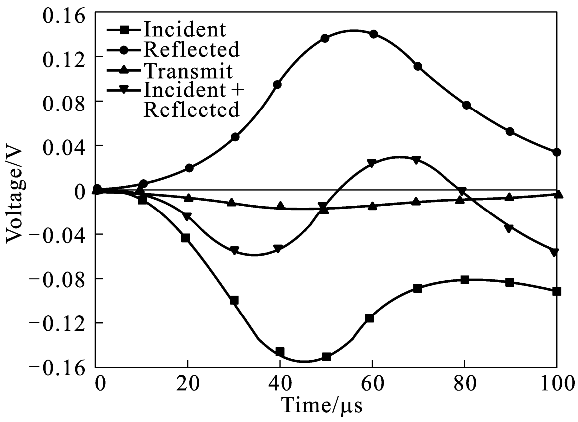

Fig. 7 Stress histories on SHPB bars in test of specimen #2

signals cannot be used to obtain tensile strength for the stress disequilibrium in this case.

From above, it can be deduced that: 1) Although the incident stress is compressive, the stresses perpendicular to the load direction are tensile in specimen. This is similar to that under static loads. 2) Stress equilibrium of specimen can be verified by the stress histories from strain gauges mounted on the specimen or the setup bars. 3) Stress histories of stain gauges on the specimen can give the time information at which the specimen cracks or the strain gauge breaks. 4) When slowly rising loads are applied, it is easier for specimen to get to stress equilibrium than that under steep wave loads.

4 Crack propagation and failure patterns of Brazilian disc under impact

Crack initiation and propagation is a key index in evaluating the validation of experimental results for Brazil tests. Generally, only those results of specimens with crack initiating from disc center and propagating along loading direction are acceptable. Under impact, the stress evolution of the specimen is highly complex. As indicated by Figs. 4 and 6, the specimen may split up with one crack through disc center with good stress equilibrium. Multiple cracks may come into form and make the failure pattern complicated when stress disequilibrium exists. In the following, some representative failure patterns are summarized based on ultra speed photography.

4.1 Center cracking with stress equilibrium

When rising stress is applied slowly, the specimen can reach stress equilibrium easily before first crack initiation in most cases, as seen in Specimen 1 mentioned above. The first crack always starts at the specimen center and spreads along the load direction. Figure 8 shows typical pictures of this kind of failure process from FASTCAM.

It can be seen that the first crack initiates at the time denoted as 0 μs. After about 20 μs, the crack propagates through the specimen along the loading direction. At about 35 μs, the two halves of specimen begin to detach from each other. The strain gauge at the center usually breaks up at this time. At 60–80 μs, the two halves of specimen would detach thoroughly. By now, the failure pattern of specimen is similar to its static counterpart with two halves neatly split up. This type of failure usually happens when the loading rates are less than 1 200 N/s.

4.2 Multiple cracks under steep-front stresses

When the impact is strong, cracks may form before stress equilibrium. And the Griffith criterion of brittle tensile failure would not be satisfied at the disc center. With the high energy carried by the stress wave and its reflection, the first crack may come into form anywhere. And secondary cracks will appear quickly after the first one but without taking the same path.

As shown in Fig. 9 with the picture series of this kind of crack propagation, the first crack initiates from the disc edge and doesn't spread along the load direction afterwards. At about 10–20 μs later, two or more secondary cracks come forth near the first crack, and they do not take the path of the first one. All these cracks dominate the failure process of specimen. The specimen fails into halves, but there is always a missing strap along the load direction in the broken specimen. This type of failure usually happens when the loading rates are between 1 000 N/s and 2 000 N/s.

4.3 Wedge failure by buckling

In tests, it is sometimes found that there are several wedge pieces of triangle shape in the broken debris. At the same time, the two halves of broken specimen are found with missing edges at the loading areas. If the two

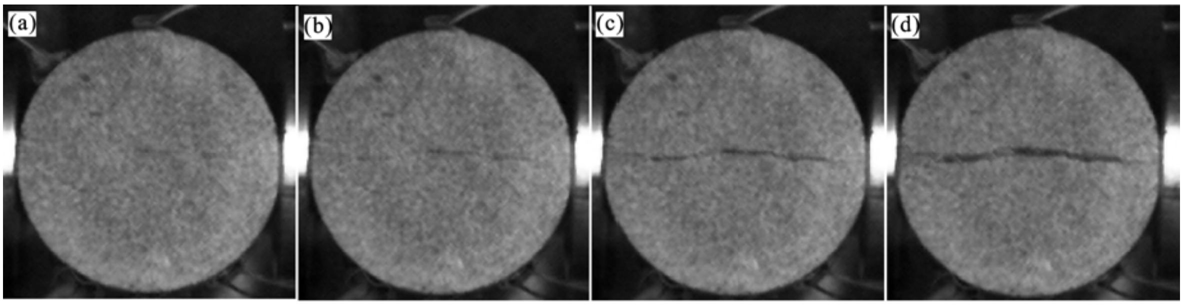

Fig. 8 Pictures for specimen failure with stress equilibrium: (a) 0 μs;(b) 20 μs; (c) 35 μs; (d) 60 μs

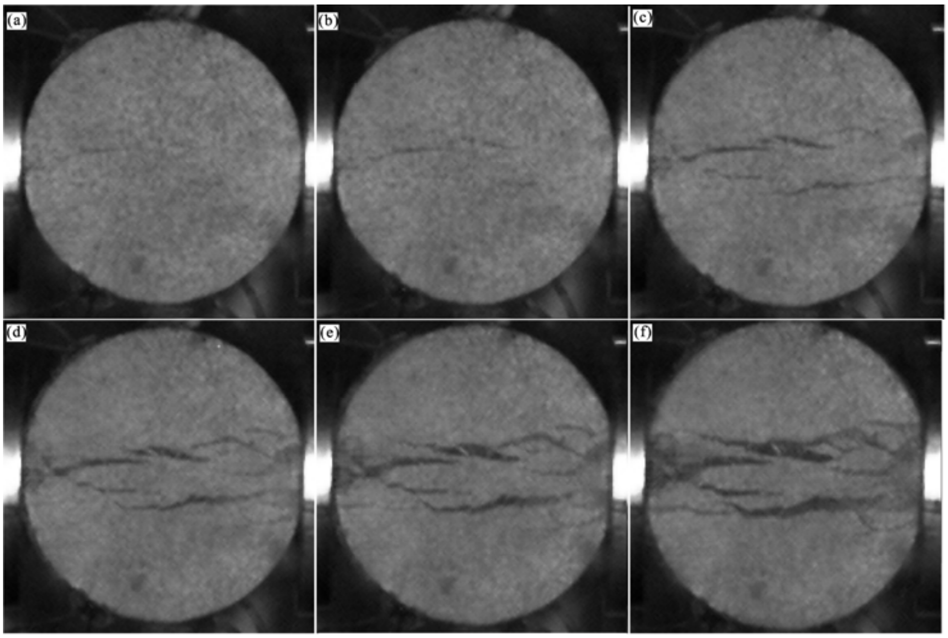

Fig. 9 Pictures for specimen failure with multiple cracks: (a) 0 μs; (b) 10 μs; (c) 50 μs; (d) 120 μs; (e) 150 μs; (f) 200 μs

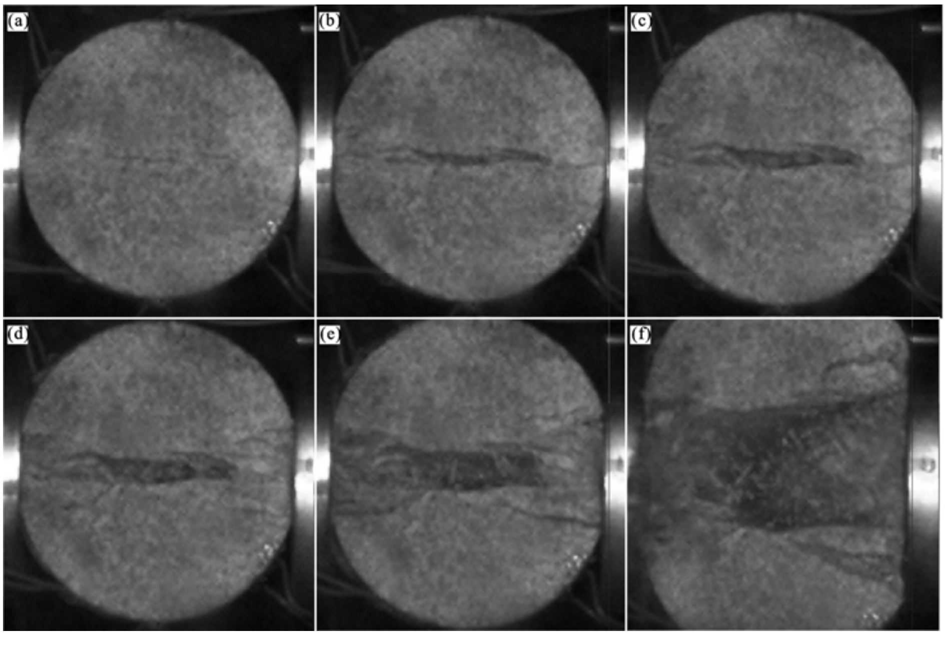

Fig. 10 Formation of broken wedges by post-failure buckling: (a) 0 μs; (b) 40 μs; (c) 80 μs; (d) 120 μs; (e) 200 μs; (f) 500 μs

halves are put together, the central parts match with each other very well. In static Brazil tests, this failure state happens when the diametrical load is so high that crushed zones appear at the contact parts of specimen and load jig. It usually makes the obtained tensile strength higher. But for the dynamic tests, the ultra speed photography reveals that the wedge failure is a post-failure behavior.

As an experimental example shown in Fig. 10, an effective tensile fracture of the specimen has been finished at about 60 μs. But as there is still incident stress in the input bar driving the bar surface to move forward, the force from the input bar makes the specimen edges buckling and broken finally at 500 μs. This type of failure usually happens when the loading rates are larger than 1 500 N/s. The failure pattern is rather deceptive for being treated as an effective part of disc splitting and being used to explain the dynamic characteristics of dynamic Brazil tests.

5 Conclusions

1) Stress distribution in Brazilian disc under dynamic loads is far more complicated than that of static cases. Stress equilibrium should be evaluated at time and space fields simultaneously.

2) Brazilian disc subjected to slowly rising stress waves tends to have good stress equilibrium. The first crack usually initiates at disc center and propagates along the load direction.

3) Brazilian disc subjected to steep-front stress waves is hard to get stress equilibrium. The first crack may appear anywhere in the specimen depending on the transient force carried by the stress waves. At the same time, lots of secondary cracks near the disc center always contribute to the missing strap of specimen along the load direction.

4) Wedge failure of specimen is actually the result of external buckling on post-failure specimen from SHPB bars.

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