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Waveform Features and Failure Patterns of Hollow Cylindrical Sandstone Specimens under Repetitive Impact and Triaxial Confinements

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Abstract: In underground engineering practice, the surrounding rocks are subjected to a nonuniform stress field with various radial gradients. In this study, a series of conventional triaxial repetitive impact tests using hollow cylindrical sandstone (HOS) specimens were conducted to reveal the impact waveform features and failure properties of rocks under nonuniform stress conditions. The tests were conducted using a modified large diameter split Hopkinson pressure bar (SHPB) testing system. The confining pressure was set as 5, 10 and 12 MPa. The data of specimens under equilibrium stress states were chosen and analyzed, and the results showed that more applied numbers of cyclic impact loads were needed to break rocks with the increase of confining pressure. Three types of cracks, i.e., ring-shaped cracks around the hole in the center of specimens, axial cracks located in the outer cylindrical surface, and lateral cracks fracturing rock fragments into small pieces appeared in HOS specimens. The failure degrees of HOS specimens could be judged by the waveform features of the reflected wave, and the waveform features of reflected wave are similar in the same failure mode, regardless of the impact velocity and the number of impacts, which only affect the failure degree.

Keywords: Hollow cylindrical sandstone; confining pressure; repetitive impact loads; reflected waveform; ring-shaped crack.

1 Introduction

The surrounding rocks near to the boundaries of underground excavation spaces are mainly under a nonuniform stress with various radial gradients, i.e., the horizontal stress σ_h of rocks located at the line AC increases from a negative value to its maximum value. Part of the rocks are subjected to a tensile stress because of rock dilatation and stress redistribution after unloading excavation activities, and the vertical stress σ_v changes from its maximum value to that of the in-situ stress (Brady and Brown 2005; Zhang and Zhao 2014), as shown in **Fig. 1**. Most failure phenomena and engineering disasters occur in the range of rocks under a nonuniform stress state, such as rock burst and slabbing (Du et al. 2016, 2020; Wang et al. 2019). Additionally, the mechanical properties of rocks under a nonuniform stress state are different from those of rocks under a uniform stress state (Wang et al. 2018); hence it is necessary to study the failure properties of rocks under uniform stresses in detail. Moreover, it is widely reported that there are various sources of dynamic loads, such as stress unloading, explosive blasting, impact loads, and vehicle vibrations during engineering excavation (Peng et al. 2019a), and the rocks around the underground spaces are subjected to a coupled static - dynamic stress state (Lee et al. 1999; Alsayed 2000; Du et al. 2016; Wang et al. 2018; Peng et al. 2019b; Wang et al. 2019). More attention must be paid to the interaction between the stress conditions and the surrounding rocks as this interaction leads to rock failures and engineering dynamic disasters.

Fig. 1 Radially nonuniform stress state of surrounding rocks of underground space: (a) Overall perspective; (b) Vertical stress; (c) Horizontal stress

It is well known that the lab tests, e.g. traditional uniaxial compression and conventional triaxial compression, are all based on the assumption of uniform distribution of stress and strain in the

rock specimens. The typical lab tests cannot reflect the effect of stress gradients and deformation constraints on the failure properties of field surrounding rocks. While lab tests using the hollow cylindrical rock specimens can realize the nonuniform stress condition of surrounding rocks through applying the internal stress, external stress and axial stress. So, it is helpful to reveal the deformation and failure mechanism of surrounding rock in underground engineering. In lab tests, the failure properties of rocks under radial gradient stress were commonly studied by using hollow cylindrical in conventional triaxial compression tests (Yang 2016), and the specimens' shape and stress path are shown in **Fig. 2**. In general, the confining stress σ_3 is applied directly by liquid pressure, and the axial stress, σ_1 , is loaded using an iron solid piston at a quasi-static loading velocity. Most studies did not consider the effect of dynamic loads, i.e., the loading rate of σ_1 , on the failure properties of rocks under radial gradient stress (Cho and Haimson 1987; Wang et al. 2019). Before testing, the hole in the specimen was blocked to prevent the liquid pressure from loading on the inner frontiers of the hole (Eugene and Robertson 1966). Through the valuable research results of quasi-static loading tests, many meaningful conclusions have been drawn. The strength of hollow cylindrical specimens under the same stress condition decreases with the increasing hole diameter (Eugene and Robertson 1966; Yang 2016), and that of specimens with the same holes increase with increasing confining pressure (Wang et al. 2018). The elastic modulus and Poisson's ratio of rock materials calculated from the hollow cylindrical specimens are more suitable to analyze the stability of deeply buried underground tunnels (Yang 2016). Through applied stress on the inner boundary of the holes, specimens in the form of hollow cylinders can be used to study the behaviors of rocks under a much wider variety of stress paths (Lee et al. 1999; Alsayed 2000; Wang et al. 2018).

Fig. 2 Testing methods of failure properties of rocks under radial gradient stress: (a) Hollow cylindrical rock specimens; (b) Stress path

Recently, Split Hopkinson pressure bar (SHPB) has become the most frequently used device to study the dynamic failure properties of rocks under different stress states (Li 2008; Xia and Yao 2019), and the dynamic loads of SHPB are with loading strain rates of 10^1 – 10^3 s⁻¹. Because of high strain rate, the dynamic loads of SHPB also are called as “impact loads.” Some tri-SHPB contained a confining pressure loading chamber and a typical one-dimensional SHPB was used to study the impact fracture properties of rocks under triaxial confinements (Bailly 2011; Tao et al. 2017; Tao et al. 2018; Wu et al. 2019). It was difficult to break rock specimens under confining pressure by one-time impact loading of the tri-SHPB, and thus, repetitive impact loads were used to inspect the dynamic properties of rocks. While it should be noted that during the process of conventional triaxial repetitive impact testing, after completing one-time impact loading, if the confining pressure is removed to check the damage degree of specimens, the specimens will experience a process of unloading-loading confining pressures (Alsayed 2002; François et al. 2014; Labiouse et al. 2014), and the mechanical properties of the rock specimens will be changed (Peng et al. 2019a; Peng et al. 2019b). Therefore, it is especially important to judge failure degree of specimens without taking the specimens out from the confining chamber during the repetitive impact loading, until their failure. The specimen failure without taking the specimen during the repetitive impact, until it is failure. As the waveform of the reflect wave can reflect the failure process of specimen during the impact process. Some researchers pointed out that the sudden increase of the signal of reflected wave means the point of failure (Zhou et al. 2011; Li et al. 2014; Lv et al. 2014). Lv et al. (2017) conducted a detail analysis on waveform curves of concrete subjected uniaxial impact loading, and classified the typical features with different loading rates. Up to now, few of investigations on the waveform features of rock like materials under confining pressure were only reported.

Hence, in this study, a series of conventional triaxial repetitive impact tests using hollow cylindrical sandstone specimens and a modified tri-SHPB testing system with a self-designed confining pressure chamber were conducted. According to the elastic theory, the radial stress of the hollow cylindrical sandstone specimens from the center hole to the periphery is a gradient transformation rather than evenly distributed. Failure properties and patterns of hollow cylindrical rock specimens under various lateral confining pressures and axial repetitive impact loads were studied. First, the difference between the incident, reflected and transmitted waves of impact loads and the stress equilibrium of intact and hollow specimens were analyzed, and then the failure pattern of rocks and the change trend of the reflected waves of different rock specimens were put forward. At last, an effective method for judging the damage and failure degree of specimens was constructed.

2 Experimental methodology

2.1 Rock specimens

A typical white sandstone was chosen and tested in this study, and three type of rock specimens were prepared, i.e., intact cylindrical specimens with a diameter of 50 mm and a height of 100 mm (Group A), intact cylindrical specimens with a diameter of 50 mm and a height of 25 mm (Group B), and hollow cylindrical specimens with a diameter of 50 mm, a height of 25 mm and a hole with a diameter of 8 mm in the center of the specimen cross-section (Group C), as shown in **Fig. 3**. The physical indices and mechanical parameters of the Group A sandstone specimens in uniaxial compression tests, i.e., p-wave velocity, v , density, ω , uniaxial compressive strength, σ_{ucs} , elastic modulus, E , and Poisson's ratio, μ , were obtained according to the suggested methods from previous literature (Du et al. 2019), as shown in **Fig. 3a**. The specimens in Group B and C were prepared for the conventional triaxial repetitive impact tests.

Fig. 3 Rock specimens used in this study

2.2 Testing apparatus

The conventional triaxial repetitive impact tests were performed through a tri-SHPB testing system with a diameter of 50 mm at Central South University, Changsha, China. A schematic diagram of this SHPB testing system is shown in **Fig. 4**. The tri-SHPB testing system is characterized as a medium and high strain rate loading apparatus, and the strain rate of the system was ranged from 10^1 to 10^3 s^{-1} . The rock specimens were put into the confining pressure vessel located between input and output bars before testing, and then the confining pressure σ_3 and axial stress σ_1 were applied to the predesigned levels. Finally, the impact stress σ_d with a half-sine

waveform along the direction of σ_1 was applied by a spindle-shaped striker. The detailed testing scheme is shown in **Table 1**.

Fig. 4 Schematic diagram of tri-SHPB testing system used in this study

Table 1 Testing design for different rock specimens in this study

Specimen Group	Confining pressure (MPa)	Gas pressure (MPa)	Specimen Group	Confining pressure (MPa)	Gas pressure (MPa)
B	5	0.7	C	10	0.6
	10	0.7		10	0.7
	12	0.7		10	0.8
C				10	0.9
	5	0.6	C	12	0.6
	5	0.7		12	0.7
	5	0.8		12	0.8
	5	0.9		12	0.9

2.3 Theory calculation

In conventional triaxial repetitive impact tests, according to the basic calculation principles of impact tests conducted by an SHPB testing system, the stress, strain, and strain rate of rock specimens under various gas pressures are calculated by Eqs. 1-3. The stress is mainly calculated by the transmitted wave, whereas the strain and strain rate are mainly calculated by the reflected wave.

$$\sigma = \frac{A_e}{2A_s} E_e [\varepsilon_I(t) + \varepsilon_R(t) + \varepsilon_T(t)] \quad (1)$$

$$\varepsilon = \frac{C_e}{L_s} \int_0^t [\varepsilon_I(t) - \varepsilon_R(t) - \varepsilon_T(t)] dt \quad (2)$$

$$\dot{\varepsilon} = \frac{C_e}{L_s} [\varepsilon_I(t) - \varepsilon_R(t) - \varepsilon_T(t)] \quad (3)$$

Where, A_e is the area of input or output bar;

A_s is the area of the rock specimen;

ρ_e is the density of the input or output bar;

C_e is the longitudinal wave velocity of the input or output bar;

L_s is the height of the tested specimen;

t is the duration of the stress wave, which is approximately 250 μ s in this study.

It must be noted that the A_s value of the hollow cylindrical specimens used in this study is the area of the outer circle minus the area of the hole.

3 Experimental results

Because the rock specimens were fixed in a confining pressure vessel during the testing process, it should be noted that the damage and failure degree of rock specimens under confining pressure during repetitive impact loading is difficult to monitor. Therefore, after several impact loading cycles, the rock specimens were taken out from the confining pressure vessel to check the damage and failure degree of rock specimens. The impact number, velocity of impact loads, and crack development condition of each specimen are shown in **Table 2**. The corresponding impact velocities of the striker are 10.89, 11.99, 13.20, and 13.90m/s under the gas pressures of 0.6, 0.7, 0.8, and 0.9 MPa, respectively. The number of impacts was randomly set during the testing process, and thus several rock specimens were kept intact when the testing was cut off. Taking the hollow cylindrical specimens under a confining pressure of 12 MPa as examples, the numbers of impact are 8, 6, 4, and 2 corresponding the gas pressures of 0.6, 0.7, 0.8, and 0.9 MPa, and the crack development conditions for SC15-12-0.6, SC16-12-0.7, SC17-12-0.8, and SC18-12-0.9 were “Intact,” “A ring-shaped crack and several axial cracks,” “A ring-shaped crack and several axial cracks,” and “A ring-shaped crack and single axial crack,” respectively.

In this study, the hollow cylindrical specimens under a confining pressure of 12 MPa show the most representative results. For these rock specimens, the main testing results are described as follows:

Table 2The number of impacts and failure patterns of different rock specimens in this study

Specimen NO.	Impact velocity (m/s)	Impact number	Crack development condition
SB1-5-0.7	11.89	3	Single axial crack
SB2-10-0.7	11.89	4	Single axial crack
SB3-12-0.7	11.89	6	Single axial crack
SC1-5-0.6	10.89	5	Single axial crack
SC2-5-0.6	10.89	6	A ring-shaped crack and single axial crack
SC3-5-0.7	11.89	2	A ring-shaped crack and single axial crack

SC4-5-0.7	11.89	2	A ring-shaped crack and single axial crack
SC5-5-0.8	13.2	2	A ring-shaped crack and single axial crack
SC6-5-0.9	13.9	1	A ring-shaped crack and several axial cracks
SC7-10-0.6	10.89	6	Intact
SC8-10-0.6	10.89	10	A ring-shaped crack and several axial cracks
SC9-10-0.7	11.89	3	Intact
SC10-10-0.7	11.89	5	A ring-shaped crack and several axial cracks
SC11-10-0.8	13.2	2	A ring-shaped crack and single axial crack
SC12-10-0.8	13.2	2	A ring-shaped crack and single axial crack
SC13-10-0.8	13.2	3	A ring-shaped crack and several axial cracks
SC14-10-0.9	13.9	2	A ring-shaped crack and several axial cracks
SC15-12-0.6	10.89	8	Intact
SC16-12-0.7	11.89	6	A ring-shaped crack and several axial cracks
SC17-12-0.8	13.20	4	A ring-shaped crack and several axial cracks
SC18-12-0.9	13.90	2	A ring-shaped crack and single axial crack

Note: In Specimen NO. the first letter indicates the specimen, the second letter indicates the sample type, the first number indicates the specimen number, the second letter indicates the confining pressure value, and the third letter indicates the impact pressure value.

3.1 Impact stress wave and equilibrium

The impact stress waves of each specimen, i.e., the incident wave, reflected and transmitted waves, were recorded by a CS-10 super-dynamic strain acquisition system, and the waves of hollow cylindrical specimens under a confining pressure of 12 MPa are shown in **Fig. 5**. For each hollow cylindrical specimen, the incident wave was controlled well with the same waveform in each impact, but the reflected and transmitted waves had a significant change with the increasing number of impacts, especially for the broken rock specimens.

In the SHPB tests, only the data of specimens under an equilibrium stress state, i.e., the stresses at the incident and transmitted ends of the specimens are equal, are valid. Hence, the stresses at the incident and transmitted ends of rock specimens under various confining pressures were calculated by Eqs. 4-5.

$$\sigma_{SI} = \sigma_I + \sigma_R \quad (4)$$

$$\sigma_{ST} = \sigma_T \quad (5)$$

Where, σ_{SI} and σ_{ST} denote the stress at the incident and transmitted ends of the rock specimens, respectively. σ_I , σ_R , and σ_T denote incident stress on the input bar, reflected stress on the input bar, and transmitted stress on the output bar, respectively.

Fig. 5 Waveform of conventional triaxial repetitive impact tests:

(a) SC15-12-0.6, (b) SC16-12-0.7, (c) SC17-12-0.8, (d) SC18-12-0.9

The stress at the incident end and transmitted end of hollow cylindrical specimens under a confining pressure of 12 MPa are shown in **Fig. 6**. It can be seen that the stress equilibrium has not been achieved before point A (approximately 45 μ s), and the stress at the incident end of the rock specimens is slightly larger than that at the transmitted end of the specimens. After the impact stress wave propagated through the specimens back and forth three times, the stresses at the specimen's incident and transmitted ends were coincident with each other that is the specimen reached a stress equilibrium condition.

Fig. 6 Stress equilibrium at specimen's two ends:

(a-b) SC15-12-0.6, (c-d) SC16-12-0.7, (e-f) SC17-12-0.8, (g-h) SC18-12-0.9

3.2 Crack type and failure pattern

The main macrocracks of hollow cylindrical specimens induced by impact in this study are classified into three types, i.e., ring-shaped cracks around the hole in the center of specimens, axial cracks located in the outer cylindrical surface, and lateral cracks fracturing rock fragments into small pieces. All specimens failed by tensile fracture. The number of ring-shaped cracks is only one for each specimen, and those of axial and lateral cracks are indefinite, which determine the fragmentation degree of rock specimens under repetitive impact. Based on the distribution of macrocracks and failure fragments, four typical impact failure patterns representing the failure degree and crack type of hollow cylindrical specimens under various confining pressures were put forward, i.e., intact, crack, breaking, and fragmentation.

Fig. 7 shows the failure patterns of hollow cylindrical specimens under a confining pressure of 12 MPa. The specimen SC15-12-0.6 remains intact without final failure after eight impacts. That is, it is difficult to damage rock specimens by impact with low velocity, i.e., 10.89 m/s (**Fig. 7a**). The specimen SC19-12-0.9 suffered a double impact with a velocity of 13.90 m/s. A single axial crack and a ring-shaped crack appeared in the specimen, and the specimen still has some load-carrying capacity (**Fig. 7b**). This phenomenon is called “crack.” The specimen SC17-12-0.8 was subjected to four impacts with a velocity of 13.20 m/s. The specimen was broken into several pieces outside the ring-shaped crack, and the length of the fragments was equal to that of the specimen (**Fig. 7c**). This failure pattern is named “breaking.” The axial cracks of SC19-12-0.9 and SC17-12-0.8 were distributed outside the ring-shaped crack. The specimen SC18-12-0.7 suffered six impacts with velocities of 11.99 m/s. The specimens were fractured into many small pieces by lateral cracks, and the axial cracks were located both inside and outside the ring-shaped crack (**Fig. 7d**). This failure pattern is named “fragmentation.” According to the aforementioned definitions, the failure patterns of other specimens under various confining pressures are shown in **Table 3**.

Fig. 7 Failure patterns of hollow cylindrical specimens under confining pressure of 12 MPa in this study: (a) intact, (b) crack, (c) breaking, (d) fragmentation

Table 3 Failure patterns of intact and hollow cylindrical specimens in this study

Specimen number	Failure patterns	Specimen number	Failure patterns
SB1-5-0.7	Crack	SC9-10-0.7	Intact
SB2-10-0.7	Crack	SC10-10-0.7	Fragmentation
SB3-12-0.7	Crack	SC11-10-0.8	Crack
SC1-5-0.6	Crack	SC12-10-0.8	Crack
SC2-5-0.6	Fragmentation	SC13-10-0.8	Breaking
SC3-5-0.7	Crack	SC14-10-0.9	Fragmentation
SC4-5-0.7	Crack	SC15-12-0.6	Intact
SC5-5-0.8	Crack	SC16-12-0.7	Fragmentation
SC6-5-0.9	Breaking	SC17-12-0.8	Breaking
SC7-10-0.6	Intact	SC18-12-0.9	Crack
SC8-10-0.6	Breaking		

3.3 Reflected wave and stress–strain curve

During the testing process, the incident wave was kept constant for the same specimen, and all specimens underwent an equilibrium stress state. **Fig. 8** shows the reflected wave and stress–strain curves of hollow cylindrical specimens under a confining pressure of 12 MPa. Eleven points, i.e., O, A, B, C, D, E, F, G, H, I, and J were defined in the reflected wave and stress–strain curves. In the reflected wave curve, A, B, C, and D represented the times when the slope of the reflected wave curve changed, and E, F, G, H, I, and J denoted the times corresponding to the reflected stress being 0 during each impact **Fig. 8 a, c, e, g**), which means the times when the specimen begins to rebound. In the stress–strain curves, A, B, C, D, E, F, G, H, I, and J are the stress/strain points corresponding to the times represented by points A, B, C, D, E, F, G, H, I, and J in the reflected wave curve (**Fig. 8 b, d, f, h**). The detailed conclusions are as follows:

Fig.8 Reflected wave and stress-strain curve of rock specimens under a confining pressure of 12 MPa: (a, c, e, g) reflected wave, (b, d, f, h) stress-strain curve. Note: the number in the figures denotes the number of punch impacts

(1) In reflected wave curve, for all hollow cylindrical specimens under a confining pressure of 12 MPa, ignoring the gas pressure and impact velocity, the corresponding times of O, A, B, C, and D were approximately 0, 45, 60, 75, and 105 μ s, respectively. The amplitude of the reflected wave

of the same specimen increases with the increasing number of impacts, except for SC15-12-0.6 (**Fig. 8a**), as no damage occurred in the hollow cylindrical specimen SC15-12-0.6, and the specimen is intact after the repetitive impact loading.

At OA stage, A was the time point for the initial stress equilibrium state. The slope of reflected wave curve changed from small to large, that is because there was no reflected wave superposition in the first 15 μ s when the impact wave propagated the back and forth through the specimen for the first time, and then the reflected wave superposition occurred (Li et al. 2014). The slope of the OA stage and the reflection stress corresponding to point A increase with the increase of the number of impacts (**Fig. 8c, e, g**).

In the AB stage, the stress equilibrium has been reached, and owing to the confining pressure, the strain rate of impact loads begins to decrease, and the deformation of specimens grows slowly. When the incident stress and the deforming stress of the specimen have the same changing rate, the specimen is under a constant strain rate loading condition (Zhou et al. 2010). In this study, the changing rate of the incident stress varies little, and that of the deforming stress of the specimens decreases. Therefore, there is a time for the changing rate of the incident stress and the deforming stress to be equal, and B in the reflected wave curve is the time when the constant-strain-rate loading condition begins (**Fig. 8**).

In the BC stage, the slope remains approximately constant. It is a constant-strain-rate loading stage. For the specimen without clear damage during repetitive impact, the constant-strain-rate loading stage is also unclear (**Fig. 8a**). As the impact velocity increases, the specimens experience microscopic damage during repetitive impact, the deformation ability of the specimens decreases, and the constant-strain-rate loading stage is obvious (**Fig. 8c, e, g**). As in the reflected wave curves in the fourth impact for SC17-12-0.8 (**Fig. 8e**) and in the sixth impact for SC18-12-0.7 (**Fig. 8g**), the reflected wave suddenly increases; this indicates that a large number of incident waves are reflected, which should be caused by the failure of the specimen (**Fig 7c, d**) (Zhou et al. 2014; Lv et al. 2017).

In the CD stage, as the compression continues, the sample deformability decreases, as the reflected wave continues to decrease. With the increasing number of the number of impacts, we can see that the rate of decline continues to decrease, even in the horizontal segment (**Fig. 8 c, e, g**).

D is the time corresponding to the peak stress at the incident end, which means that the elastic energy stored in the specimens begins to release after D point. DE, DF, DG, DH, DI, and DJ denote the same stage in the reflected wave curve for different the number of impacts, which are the unloading stages for the rock specimens. The slope of the DE / DF / DG / DH / DI / DJ stage is

slightly steeper than that of the CD stage, and the failure degree of the rock specimens can also be reflected in the variation in the slope of the unloading stages and the time when the specimen begins to rebound with the number of impacts. This can be divided into three main categories, as follows:

(a) Under the relatively low-pressure impact of this experiment, the slope of the unloading stages and the time when the specimen begins to rebound are almost the same; there is no change with the increasing number of impacts (**Fig. 8a**) and the specimen is still intact after repetitive impact (**Fig. 7a**).

(b) The slope of the unloading stage first decreases and then increases. In the first three impacts of SC15-12-0.7 (**Fig. 8g**), as SC15-12-0.6, the slopes of the unloading stage at the time when the specimen begins to rebound are almost consistent. This means that there is no or little damage in the specimen during these impacts, and then the slope of the unloading stage in the reflected wave on the fourth impact is less than that in the previous impact and the time when the specimen begins to rebound extends significantly. This should be caused by the microscopic damage developed during the impact that reduced the elastic modulus of the specimens. The slope of the unloading stage in the reflected wave increases rapidly in the fifth and sixth impacts, and exceeds that in the first three impacts. Additionally, the time when the specimen begins to rebound continues to increase. As mentioned above, the macrocracks appear in the specimen during the fifth and sixth impacts, which would accelerate the stress unloading.

(c) The slope of the unloading stage and the time when the specimen begins to rebound continue to increase with the number of impacts (**Fig. 8c, e**). This should be caused by the increasing impact pressure, thereby accelerating the development of microcracks and macrocracks of the specimen.

(2) In the stress–strain curves, the slopes of AB, BC, and CD decrease continuously for all specimens under various gas pressures, which is consistent with the slope change trend in the reflected wave curves. In the unloading stages, i.e., DE, DF, DG, DH, DI, and DJ, for the specimen without clear damage during repetitive impact, the curve rebounds clearly (**Fig. 8b**); for the specimens experiencing clear damage during repetitive impact, the curve rebound is no longer observed (**Fig. 8d, f, h**). Owing to the confining pressure effect, there is a certain load capacity for the specimens with final failure (**Fig. 8d, f, h**). From **Fig. 8d, f, h**, we can see that the stress–strain curve changes from Class I: significant unloading stage in association with stored elastic energy release to Class II: unrecoverable dissipations drive successive deformation (Li et al. 2018), and the portion of DE, DF, DG, DH, DI, and DJ increases with number of impacts. The peak strain for the same specimen increases with number of impacts, and the strength for the same specimen decreases with number of impacts.

4 Discussion

4.1 Reflected wave and failure pattern

Some researchers have pointed out that the sudden increase in the reflected wave indicates the point of rock failure (Zhou et al. 2010; Lv et al. 2017); that is, the reflected wave of impact loads have a significant relationship with the failure patterns of specimens during impact loading. At present, the investigations on reflected wave features and failure patterns of rocks, are rare especially on the relationship between reflected waves and failure pattern of rocks under confining pressure. As mentioned above, the experimental results in this study showed that the features of the reflected waveform curve are very important to judge the failure of the specimen.

First, the reflected wave curves of different specimens were compared and analyzed. **Fig. 9** shows the similar reflected waves of hollow cylindrical specimens during repetitive impact loading. As shown in the **Fig. 9a**, under a confining pressure of 12 MPa, the changes in the reflection stress of the four curves with time are similar, although the impact pressure and the number of impacts are different, which is very common in experiments. Because these all occur during cyclical impact, they have a higher amplitude, a slower changing in slope of the unloading stage, and a later time to rebound than the curve of the specimens without damage after impact, such as the reflected wave of SC15-12-0.6, SC17-12-0.7 in the first three impacts, and SC17-12-0.8 in the first two impacts. However, they have a smaller amplitude, a slower changing in slope, and an earlier time to rebound than the curve of the specimens is failed after impact, such as the reflected wave of SC17-12-0.7 in the fifth and sixth impacts, SC17-12-0.8 in the fourth impact, and SC18-12-0.9 in the second impact. Therefore, the reflected wave in **Fig. 9a** is between the reflected wave of the specimen without damage and that of the specimen with macrocracks after impact. We believe that the microcracks of the specimen have developed by this time. To confirm this, we conducted a comparative test. The solid black line in the **Fig. 9a** is the reflected wave curve of the third impact of the specimen under the impact velocity of 13.20 m/s with a confining pressure of 12 MPa. After the impact is completed, the specimen is still intact, see **Fig. 7a**, but there is very slight spalling at the local surface. When a similar reflected wave curve appears, it is impossible to determine whether the specimen has a microcrack. As the waveforms are not significantly different, the later the time when the specimen begins to rebound, the more obvious the development of the microcracks. Therefore, we compared this type of curve with the reflected wave curve of SC15-12-0.6. It was found that the waveform is similar, but it changed slowly with time, and the time at which the specimen begins to rebound from the point D is approximately the time when the stress wave has transmitted back and forth three times in the specimen.

Fig.9 Similar waveforms of hollow cylindrical sandstone specimens (a) intact but damaged, (b) longitudinal crack, (c) breaking

In **Fig. 9b**, after the constant-strain-rate loading section passed, the reflected wave should have decreased. However, it almost changes horizontally until the peak stress passes, when it begins to decrease, the slope of the unloading stage becomes steeper, and the time at which the specimen begins to rebound is far from the peak stress at the incident end, as shown in **Fig. 8c** and **Fig. 8g**. As **Fig. 7b** shows, there is a crack in the axial direction and a similar ring-shaped crack around the hole, as indicated by the red marker line. As mentioned above, the rise of the reflected wave indicates that the specimen has a macroscopic crack during the repetitive impact. It can be seen from **Fig. 7b** that the crack of the specimen is approximately parallel to the axial direction, although there are some fluctuations. Owing to the presence of the confining pressure, the lateral clearance of the crack is smaller during the impact process. Therefore, the incident wave is not reflected much by such a crack. Compared with the reflected wave-time curve of the intact sample, the reflection wave is elevated, but it is relatively gentle. We thus infer that when the reflected wave appears to have a long and gentle decline, and the time when the specimen begins to rebound is far from the peak stress at the incident end, the specimen should have a crack approximately parallel to the axial direction.

From the **Fig. 9c**, we can see that the reflected wave had a rapid rise in the constant-strain-rate loading section and then slowly decreased. In this way the time at which the specimen begins to rebound from the peak stress at the incident end continued to increase. Referring to **Fig. 7c** and **Fig. 7d**, it can be observed that in both cases, multiple shear cracks and shear planes appear after the specimen fails. The occurrence of shear cracks and shear planes causes a many incident waves to reflect, thus sharply increasing the reflected waves. If the impact velocity is large enough, the reflected wave will rise more sharply and a “double-peak” phenomenon will occur (Hokka et al. 2016), which can also be observed under uniaxial compression conditions (Li et al. 2014; Lv et al. 2017).

In addition, from **Fig. 9**, we found that under the same confining pressure conditions, although the impact velocity and the number of impacts are different, when the impact results are similar, for

example, damage occurs, axial cracks occur, or shear planes appear, the waveform and size of the reflected waves are similar. It should be pointed out that the impact velocity and the number of impacts affect the degree of damage but do not change the failure mode, as shown in **Fig. 7c** and **Fig. 7d**. However, although we only analyzed the case where the confining pressure is 12 MPa, a similar phenomenon can be observed under confining pressure conditions of 5 and 10 MPa, as shown in **Fig. 10**. From this figure, it was found that under different confining pressures, for the same failure mode, the waveform features of the reflected wave are similar, although there are some subtle differences with increasing confining pressure. As shown by the reflected wave of SC14-10-0.9 in **Fig. 10c**, at lower confining pressure and high-speed impact, a “double peak” phenomenon appears in the reflected wave. We conclude that under confining pressure, the waveform of the reflected wave can reflect the failure mode of the specimen during repetitive impacts.

Fig. 10 Waveforms of hollow cylindrical specimen under different confining pressure: (a) longitudinal crack, (b) breaking, (c) fragmentation

The above analysis is mainly for hollow cylindrical specimens, but even with different confining pressures, the laws of the reflected wave change with time are similar, and this also applies to conventional specimens. **Fig. 11** shows the waveform feature of a specimen under the impact velocity of 10.89 m/s with different confining pressures. Compared with the hollow cylindrical specimen, under different confining pressures, the changes with time of the waveform feature of the conventional specimen are similar, whereas the degree of stress reduction and the time the specimen begins to rebound are relatively earlier, as shown in **Fig. 11b**. This may be due to the existence of a hole, and the holes allowed a greater deformation of the specimen in the radial direction (Xia and Yao 2015). Owing to the small size of the hole, the deformability provided by the free faces of the hole is limited; it is not obvious with the increasing confining pressure, which is consistent with the experimental phenomenon. As the failure mode of conventional specimen is

dominated by compression and shear (Lu and Li 2011; Zhou et al. 2016), as shown in Fig. 12, and owing to the shear plane, the reflected wave had a rapid increase and showed the “double-peak” phenomenon.

Fig. 11 Reflected waveform curve of specimen under gas pressure of 0.6 MPa and different confining pressures: (a) hollow cylindrical specimens, (b) intact specimens

Fig.12 Waveform feature and failure mode of conventional specimen

4.2 Ring-shaped cracks in hollow cylindrical specimens

It was found that a typical ring-shaped crack appeared in the broken hollow cylindrical specimen, and this was different from that of the intact specimens in conventional triaxial impact tests. A simple explanation for the typical ring-shaped cracks was proposed based on the elastic mechanics theory in this study. The stress state of the hollow cylindrical specimens is mainly affected by the impact load and confining pressure, and the stress distribution caused by the impact load and confining pressure can be expressed as shown in Eq. 6 and Eq. 7, respectively. According

to the superposition principle, the coupled stress distribution of the hollow cylindrical specimen superimposed by Eq. 6 and Eq. 7 can be expressed as in Eq. 8:

$$\left. \begin{aligned} \sigma_r^1 &= -\frac{\mu}{1-\mu} P \left(1 - \frac{r_0^2}{r^2}\right) \\ \sigma_\theta^1 &= -\frac{\mu}{1-\mu} P \left(1 + \frac{r_0^2}{r^2}\right) \\ \sigma_z^1 &= -P \end{aligned} \right\} \quad (6)$$

$$\left. \begin{aligned} \sigma_r^2 &= -P_0 + \frac{r_0^2}{r^2} P_0 \\ \sigma_\theta^2 &= -P_0 - \frac{r_0^2}{r^2} P_0 \\ \sigma_z^2 &= -2\mu P_0 \end{aligned} \right\} \quad (7)$$

$$\left. \begin{aligned} \sigma_r &= \frac{r_0^2}{r^2} \left(P_0 + \frac{\mu}{1-\mu} P\right) - \frac{\mu}{1-\mu} P - P_0 \\ \sigma_\theta &= \frac{r_0^2}{r^2} \left(-P_0 - \frac{\mu}{1-\mu} P\right) - \frac{\mu}{1-\mu} P - P_0 \\ \sigma_z &= -P - 2\mu P_0 \end{aligned} \right\} \quad (8)$$

where σ_r is the radial stress, σ_θ is the hoop stress, σ_z is the axial stress, r is the radial distance from a certain point to the center of the hole in the specimens, r_0 is the radius of the hole in specimens, μ is the Poisson's ratio of the rock, P is the impact load, and P_0 is the confining pressure.

The stress distribution of hollow cylindrical specimen is a plane strain problem (Timoshenko and Goodier 2003). According to Hooke's law and Eq. 8, the strain distribution of hollow cylindrical can be expressed as in Eq. 9:

$$\left. \begin{aligned} \varepsilon_r &= \frac{1-\mu^2}{E} \left[\sigma_r - \frac{\mu}{1-\mu} (\sigma_\theta + \sigma_z) \right] \\ \varepsilon_\theta &= \frac{1-\mu^2}{E} \left[\sigma_\theta - \frac{\mu}{1-\mu} (\sigma_r + \sigma_z) \right] \\ \varepsilon_z &= \frac{1-\mu^2}{E} \left[\sigma_z - \frac{\mu}{1-\mu} (\sigma_r + \sigma_\theta) \right] \end{aligned} \right\} \quad (9)$$

Where, ε_r is the radial strain, ε_θ is the hoop strain, ε_z is the axial strain, and E is the elastic modulus.

Taking specimen SC3-5-0.7 as an example, the stress and strain were calculated and shown in **Fig. 13**. The law of σ_r , σ_θ , σ_z , ε_r , ε_θ and ε_z which is changed with time is similar to the law of impact load which is changed with time. The maximum absolute values of σ_r , σ_θ , σ_z , ε_r , ε_θ and ε_z are obtained at the time corresponding in the peak of the impact load. In addition, σ_r , σ_θ , ε_r , and ε_θ can

significantly vary with the changes in r . Owing to the axial symmetry of hollow cylindrical specimens, the specimens experience a progressive dilatation along the radial direction during the impact loading, and it can be inferred that the ring-shaped cracks have a close relationship with the radial deformation. In this ways, the evolution law of the radial deformation of hollow cylindrical specimens, u_r , is analyzed as follows (Timoshenko and Goodier 2003):

$$u_r = r\epsilon_\theta \quad (10)$$

According to Eq. 10, the u_r of specimen SC3-5-0.7 versus time and r can be obtained as presented in **Fig. 13**. There is a clear location where u_r of specimens under a confining pressure of 5 MPa changes from a negative value (tensile displacement) to a positive value (compressive displacement). The distance between the zero point of u_r and the center of the hole in hollow cylindrical specimens is approximately 13 mm, as shown in **Fig. 14b**. The hollow cylindrical specimens can be divided into two parts, i.e., the tensile zone and compressive zone, and the demarcation line between these zones moves toward the boundary of the specimen as the confining pressure increases.

Consequently, to reflect the radial displacement changes with r more intuitively, the relationship of the maximum displacement with r is analyzed. It can be seen from **Fig. 14b** that the ring-shaped crack is located at the demarcation line between the tensile and compressive zones, and the theoretical calculated value is approximately the same as the position of the ring-shaped crack on the failure specimens in this study. Because only an elastic analysis is performed and the rock specimen also has inhomogeneity, the theoretically obtained ring-shaped crack cannot completely coincide with the experimental results. It should be pointed out that the ring-shaped crack phenomena are rarely observed under static loading, and thus it is concluded that the phenomenon of ring-shaped cracks is the result of a combination of a radial gradient stress and high-strain-rate loading, and this requires further research and analysis. In addition, it can be seen from the **Fig. 14b** that there is a tensile displacement outside the demarcation line, combining Eq. 10 shows that there is a circumferential tensile strain between the ring-shaped crack and the edge of the specimen, which is why there is always an axial crack, as can be seen from **Fig. 7** and **Fig. 10**.

With respect to the zonal disintegration phenomenon of deep rock subdivisions, many studies have been conducted on numerical simulations, similar materials and theoretical analysis, and a large number of conclusions have been drawn. However, the failure mode in the test in this study showed that the zonal disintegration phenomenon can occur when using cyclic impact on sandstone under radial gradient stress, it proves that the stress state of the surrounding rock excavation can be simulated to a certain extent in the hollow cylindrical rock test once again.

Fig. 13 Stress and strain as a function of time and r

Fig. 14 (a) U_r of specimen SC3-5-0.7; (b) U_r (max) versus radius under impact loads with velocity of 11.89 m/s

5 Conclusions

In this study, a series of conventional triaxial repetitive impact tests using hollow cylindrical specimens were conducted. In the testing, the impact loads were induced by different gas pressures of 0.6, 0.7, 0.8, and 0.9 MPa and the confining pressures were set to 5, 10, and 12 MPa. The features of the impact wave, crack type, and fracture pattern were analyzed, and the main conclusions are as follows:

- (1) Hollow cylindrical sandstone specimens under cyclic impact loads by SHPB also experienced equilibrium stress states, and the hole in the specimens have no influence on the equilibrium stress states of the specimens.
- (2) The main macrocracks of hollow cylindrical specimens induced by impact loading are ring-shaped cracks around the hole in the center of specimens, axial cracks located in the outer cylindrical surface, and lateral cracks fracturing the rock fragments into small pieces. Based on the distribution of macrocracks and failure fragments, four typical impact failure patterns representing the failure degree and crack type of hollow cylindrical specimens under various confining pressures were proposed, i.e., intact, crack, breaking, and fragmentation.
- (3) If the crack development condition and failure pattern of hollow cylindrical specimens are similar, the waveform and size of reflected are similar. It should be pointed out that the impact velocity and the number of impacts can affect the degree of damage but cannot change the failure mode.
- (4) By using elastic mechanics analysis, it is found that there are stretching and compression zones in the radial direction of hollow cylindrical specimens, and the boundary line between them easily leads to the formation of ring-shaped cracks.

Data Availability Statement

The datasets generated for this study are available on request to the corresponding author.

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Manuscript number GGGG-D-20-00099

Responses to the editors' and reviewers' comments

Dear Editors and Reviewers:

Thank you very much for giving us this opportunity to revise our manuscript. Further, we appreciate the helpful corrections and suggestions from the reviewers. We have revised our manuscript carefully based on the comments. The revised parts have been marked in **RED** color in the manuscript, and the marked copy of it have been included at the end. The main corrections and responds to the comments are as follows:

Responses to the editors' comments:

Response to: I do not see much scientific discussion in the paper and I would encourage authors to discuss detailed findings. There are quite few papers authors have missed out from this journal and I suggest authors to read and cite if appropriate.

Response: Thank you for your comment. We have tried our best to discuss detailed findings according to the editors' comments and added detailed findings. We have also cited a few new articles of the journal in various sections to improve the quality of the present work.

Lee B, Rathnaweera T D (2016) Stress threshold identification of progressive fracturing in bukit timah granite under uniaxial and triaxial stress conditions. Geomech Geophys Geo-Energy Geo-resour, 2(4): 301-330. <https://doi.org/10.1007/s40948-016-0037-z>.

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Yang, SQ, Yang J, Xu P (2020) Analysis on pre-peak deformation and energy dissipation characteristics of sandstone under triaxial cyclic loading. Geomech Geophys Geo-Energy Geo-resour 6(24):1-15. <https://doi.org/10.1007/s40948-020-00146-0>.

Responses to the reviewer' comments:

Reviewer #1:

1. Response to comment: State the mineralogy of used rock specimens

Response: Thank you for your valuable comment. It has been described in the revised manuscript as follows,

...and microscope examination was performed to determine the mineralogical composition and grain sizes of the sandstone, as shown in Fig.3, which has a primary mineral composition of Quartz (~ 38%, grain size 0.005-0.5 mm), Plagioclase (~ 28%, 0.005-0.5 mm), K-feldspar(~ 10%,0.005-0.5 mm) and other chink (~ 24%, 0.002-0.3 mm). Modifications can be found in lines 116-120 in the revised manuscript.

Fig. 3 Optical microscope photomicrographs showing mineral compositions of sandstone

2. Response to comment: What is the reason for not providing different gas pressures on specimen group B.

Response: Thank you for your valuable comment. The specimen group B (traditional specimen), the radial stress of which under confining pressure is evenly distributed, and for comparison with impact waveform features and failure properties of rock under nonuniform stress conditions, a confining pressure impact test using specimen group B under the same conditions were performed. Through the previous series of tests, we found that the gas pressure mainly affects the damage degree of the specimen and the number of impacts required for the damage of the sample but has

little effect on the waveform characteristics and the failure mode. Therefore, we did not consider different gas pressures in the comparison test. Modifications can be found in lines 112-123 in the revised manuscript.

3. Response to comment: In the methodology, state clearly, whether you can detect the sample failure stage without taking the sample out of the set-up.

Response: Thank you for your valuable comment. We have described the method in detail according to the Reviewer's comments. Modifications can be found in lines 417-433 in the revised manuscript.

4. Response to comment: Please use appropriate terms in the manuscript

Eg- Line 54

Use "laboratory" instead of "lab"

Response: Thank you for your valuable comment. We have made correction according to the Reviewer's comments.

5. Response to comment: General comments

There are unclear sentences. Please check them.

Eg- Line 96

"The specimen failure without taking the specimen during the repetitive impact, until it is failure."

There are grammar mistakes. Please check them.

Response: Thank you for your valuable comment. We have rewritten it according to the Reviewer's comments. Modifications can be found in lines 90-92 in the revised manuscript.

Eg- Line 101

"Up to now, few of investigations on the waveform features of rock like materials under confining pressure were only reported" should be corrected as "Up to now, a few investigations were only reported on the waveform features of rock-like materials under confining pressure"

Response: Thank you for your valuable comment. We have made correction according to the Reviewer's comments. Modifications can be found in lines 100-101 in the revised manuscript.

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Revised manuscript with tracked changes
revised-manuscript.doc

This piece of the submission is being sent via mail.