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Experimental study of the dynamic shear response of rocks using a modified punch shear method

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Abstract: Cohesion and internal friction angle are the two material parameters used in the Coulomb model to predict rock failure in many rock engineering applications. Although these two parameters have been extensively quantified under static conditions using the direct shear or the triaxial compression methods, the effect of dynamic loading on these parameters is not yet clear. A dynamic punch shear method was proposed by Huang et al. in 2011 to measure the dynamic cohesion of rocks, and the dependence of cohesion on the loading rate has been revealed. To further investigate the effect of dynamic loading on the internal friction angle and thus the complete dynamic shear response of rocks, this method is extended in this study to include the normal stress by applying lateral confinement to a disc specimen. The confinement is realized by enclosing the specimen assembly in a 1.5 inch diameter Hoek cell. The dynamic load is applied by a split Hopkinson pressure bar (SHPB) system, which is modified to ensure that the specimen assembly remains intact in the Hoek cell during pressurization by applying a static axial pre-stress. Three groups of green sandstone specimens under confinements of 0, 10 and 20 MPa are tested with different loading rates. The results show that the dynamic shear strength exhibits significant rate dependency and it thus increases with the loading rate and the normal stress. The dynamic cohesion increases with the loading rate, while the internal friction angle remains constant.

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List of symbols

GS	Green sandstone
ISRM	International Society for Rock Mechanics and Rock Engineering
MTS	Material test system
PS	Punch shear
PTS	Punch through shear
SHPB	Split Hopkinson pressure bar
BPI	Block punch index
A	Cross-sectional area of bars (mm^2)
B	Thickness of the punch shear specimen (mm)
C_0	Cohesion of rock (MPa)
D	Diameter of the bars (mm)
E	Young's modulus of the bars (GPa)
F_1	Total force on incident end of the punch shear specimen (N)
F_2	Total force on transmitted end of the punch shear specimen (N)
P_1	Force on incident end of the punch shear specimen due to stress wave (N)
P_2	Force on transmitted end of the punch shear specimen due to stress wave (N)
p_0	Hydrostatic confining pressure (MPa)
τ_s	Shear strength of the green sandstone specimen (MPa)
c	One dimensional stress wave speed of the bar (m/s)
v_0	Velocity of the striker (m/s)
ρ	Density of the bars (kg/m^3)
σ_{nor}	Normal stress applied on the specimen shear surface (MPa)
σ_{pre}	Axial pre-stress (MPa)
μ	Coefficient of internal friction
ϕ	Internal friction angle of rock ($^\circ$)

ε_i	Incident wave in strain
ε_r	Reflected wave in strain
ε_t	Transmitted wave in strain
$\dot{\tau}$	Loading rate of the dynamic punch shear test (GPa/s)
α	Fitting parameter

1 Introduction

Shear failure is one of the most important failure modes encountered in practical problems in rock engineering. Shear strength that describes the material resistance to shear load is thus a crucial mechanical rock property to predict the failure of rocks and rock-like materials. It has been widely used in engineering designs and the mitigation of geo-hazards (ASTM 2008a; ASTM 2008b; Cen and Huang 2017; Huang et al. 2011).

As one of the most widely used shear failure criteria in geotechnical engineering and numerical modeling (Jaeger et al. 2009), the Coulomb strength criterion suggests that the shear strength is equal to the sum of the cohesion C_0 and the normal stress σ_{nor} acting along the shear failure plane multiplied by the coefficient of internal friction μ . The cohesion of the rock is determined as the shear strength without normal stress, while the other parameter in the Coulomb criterion, the coefficient of internal friction μ , or equivalently the internal friction angle ϕ ($= \tan^{-1}\mu$), can be obtained by conducting shear tests with normal stresses (Jaeger et al. 2009). The Coulomb criterion has been recently extended to rock engineering applications where rocks are subjected to dynamic loadings (Huang et al. 2011). In this extension, the internal frictional angle ϕ was determined using static experimental data and it was assumed that ϕ is independent of the loading rate (Yao et al. 2017). This postulation has indirect support from experimental and theoretical studies (Li et al. 2000; Li et al. 1999; Zhao 2000). However, direct experimental verification is desirable.

Amongst many other different types of shear tests, there are two common methods to quantify the static shear strength of brittle solids: the direct shear test and the triaxial compression test. Using the triaxial compression test, the two Coulomb criterion parameters can be determined by plotting the envelope of all Mohr's circles that correspond to stress

states at failure. In the Coulomb theory, the envelope is assumed to be a straight line in the $(\sigma-|\tau|)$ plane that intercepts the $|\tau|$ -axis at C_0 and has a slope μ (Jaeger et al. 2009). Unlike the triaxial compression test, the direct shear test can be used to directly measure the shear stress along the shear failure plane and there are two common methods in this category: the direct shear-box test and the punch test. The direct shear-box test is applicable mainly to rock joints (Jang et al. 2018), and it has been proposed as one of the suggested methods by the International Society for Rock Mechanics and Rock Engineering (ISRM) (Ulusay and Hudson 2007). The punch test was originally proposed for determining the direct shear strength of disc rock specimens while employing a simpler apparatus (Stacey 1980), in which the compressive load produces shear failure surfaces along the loading direction in the specimens (Lama and Vutukuri 1978; Mazanti and Sowers 1966; Stacey 1980). Different types of punch head lead to different shear failure surfaces: circular surfaces from punch shear tests and planar surfaces from block punch tests (Fig. 1). Depending on the geometry of the specimen, the punch test using the circular punch head can be further divided into two types: the punch shear (PS) test in which a thin disc specimen is used (Fig. 1a) and the punch through shear (PTS) test a cylinder specimen with two circular notches is used (Fig. 1b). Studies on the block punch test (Fig. 1c) have led to the development of the block punch index (BPI) test (Schrier van der 1988; Sulukcu and Ulusay 2001; Ulusay and Gokceoglu 1997), which was designed to accommodate the specimen in the frame of a point load testing device. The BPI value was then calculated by dividing the maximum load by the shear failure surface area. Many types of rocks have been tested to investigate the size effect of the test specimen and a size-corrected BPI has been proposed and related to uniaxial compressive strength (UCS). The BPI test later became one of the ISRM suggested methods (Gaziev 1979; Ulusay 2014).

Fig. 1 Different types of punch tests: (a) punch shear (PS) test, (b) punch through shear (PTS) test, (c) block punch test.

In geotechnical engineering and geophysics applications involving different scales, rocks may be subjected to dynamic loading due to drilling, blasting, landslides or earthquakes (Xia and Yao 2015; Zhang and Zhao 2014). It is thus desirable to develop a method to determine the dynamic shear strength of rock materials. Since Kolsky developed the split Hopkinson pressure bar (SHPB) system in 1949 (Kolsky 1949), it has been extensively applied to quantify dynamic mechanical behavior of brittle solid materials at high loading rates (Xia and Yao 2015). Recently, the SHPB has been suggested as the standard tool to measure the dynamic compressive strength, tensile strength, and fracture toughness of rocks by the ISRM (Zhou et al. 2012). Using the modified SHPB, Huang et al. (2011) developed a dynamic PS method to quantify the dynamic shear properties of Longyou sandstone. This development followed attempts to investigate the dynamic shear response of ductile materials using the SHPB in combination with the PS method, such as metals (Dabboussi and Nemes 2005; Qu et

al. 2005) and fiber composites (Li et al. 2002). Later, shear properties of various rock and rock-like materials such as Fangshan marble (Yao et al. 2017) and concrete (Grima et al. 2015) were studied by employing the modified SHPB combined with the PS method.

It is generally accepted that the PS testing results are comparable to the shear strength with zero confinement (Jaeger 1979). Based on this assumption, the dynamic punch with the SHPB tests can be used to determine the cohesion of the rock. The results indicated that the cohesion increases with the loading rate (Huang et al. 2011; Yao et al. 2017).

The above studies were only concerned with the rate dependence of the cohesion of the rock. To study the effect of loading rate on both the cohesion and the internal friction angle of Bukit Timah granite, Zhao and his coworkers (Li et al. 2000; Li et al. 1999; Zhao 2000; Zhao et al. 1999) conducted shear tests with the loading rates ranging from 5×10^{-5} to 200 GPa/s using a modified triaxial compression machine. They came to the conclusion that the cohesion is rate dependent while the internal friction angle is not. However the details of the experimental method were not clearly presented in the open literature and the range of the loading rates is limited.

An alternative way to investigate the effect of loading rate on the internal friction angle is to apply lateral confinement in the dynamic circular punch tests. Lukić and Forquin (2016) conducted a series of PTS experiments on an ultra-high performance concrete in the quasi-static and dynamic regimes. A metal ring was used to enclose the cylindrical specimen to induce the normal stress on the specimen during dynamic axial compression. However, the resulting normal stress varied during the loading, and the interpretation is therefore difficult.

Following the idea of Lukić and Forquin (2016) while achieving a controlled normal stress, this study introduces a modified PS method with static lateral confinement. The confinement is realized by enclosing the specimen assembly in a 1.5 inch diameter Hoek cell. The dynamic load is applied by an SHPB system, which is modified to ensure that the specimen assembly remains intact in the Hoek cell during pressurization by applying a static axial pre-stress.

To fully understand the dynamic shear mechanism, microscopic observation of the

failure pattern is necessary. The 2D microscopic observation techniques involve specimen cutting and polishing (Huang et al. 2013). X-ray computed tomography (CT) on the other hand provides a non-destructive method in medical and industrial applications (Charalampidou et al. 2011; Otani and Obara 2004). Thus in this study, the 3D X-ray micro CT technique is used to observe the shear failure surfaces and the internal cracks of the tested specimens.

The purpose of this paper is to investigate the rate dependence of the shear failure of a chosen rock (green sandstone from Sichuan, China) within the theoretical framework of the Coulomb strength criterion. Specifically, the rate dependence of the two parameters in the Coulomb model is investigated using the modified PS method with the SHPB. This paper is organized as follows. After the introduction, the dynamic punch shear device and the working principles are presented in Section 2. The validity and flexibility of the method are systematically discussed by applying it to green sandstone (GS) in Section 3. Section 4 presents the experimental results, including the physical meaning of the dynamic shear strength. Main conclusions are drawn in Section 5.

2 Specimen preparation and experimental methodology

2.1 Specimen preparation and assembly

To manufacture the disc specimen for the PS test, rock cores with a nominal diameter of 38 mm were drilled from the same rock block along the same orientation. These cores were then sliced into thin discs with thickness of 15 mm. The end surfaces of the disc specimen were carefully polished to achieve a surface roughness of 0.5% and straightness to ± 0.02 mm over the full thickness according to the ISRM suggested methods (Zhou et al. 2012).

The apparatus for PS tests is composed of two parts: a cylindrical punch head and a holder or rear supporter (Backers et al. 2002). The schematic of the PS specimen assembly is shown in Fig. 2a. The punch head in this device is the incident bar with a diameter of 25.4 mm, the rear supporter is attached to the transmitted bar. The inner diameter of the rear supporter is 25.8 mm, 0.4 mm larger than the diameter of the punch head based on the existing design (Huang et al. 2011). Ideally, the punch head dimension should match that of

the rear supporter. However, the clearance of 0.4 mm is necessary to accommodate potential errors in machining and specimen fabrication. As a result, the rock plug produced by the punch action can be successfully recovered in the hole of the rear supporter (Huang et al. 2011). The compressive axial load produces a cylindrical shape shear failure surface in the tested specimens.

A Hoek cell is used to apply uniform lateral confinement on the side surface of the disc specimen, which causes constant normal stress along the shear failure surface. The schematic of the PS specimen assembly in the Hoek cell is shown in Fig. 2c. The incident bar is brought into contact with the PS specimen through a guide tube (Fig.2b). The guide tube has an outside diameter of 38 mm, the same as the outside diameter of the specimen assembly, and an inner diameter of 25.6 mm, 0.2 mm larger than the diameter of the incident bar. Consequently, the guide tube is subjected to the lateral pressure exerted by the Hoek cell membrane and ensures free sliding of the incident bar inside.

Fig. 2 Schematic of the punch shear specimen assembly with lateral confinement: (a) the punch shear specimen assembly; (b) the guide tube; (c) the Hoek cell enclosing the punch shear specimen.

2.2 Modified split Hopkinson pressure bar (SHPB) system

Using the specimen assembly shown in Fig. 2, static punch shear tests were conducted, in which the incident bar and transmitted bar were replaced by much shorter steel bars with a diameter of 25.4 mm. The SHPB system was employed to conduct the dynamic PS tests. The experimental apparatus was suggested by the ISRM for dynamic rock tests (Zhou et al. 2012), and consists of a striker bar, an incident bar, and a transmitted bar (Fig. 3). All bars are made of high strength maraging steel (25.4 mm in diameter), whose physical and mechanical properties are summarized in Table 1. The lengths of the incident, the transmitted and the striker bars are 1800 mm, 1500 mm and 200 mm, respectively.

Fig. 3 Schematics of the modified SHPB system with the Hoek cell enclosing the PS specimen assembly. The top insert illustrates the operational mechanism of the system.

It is worth noting that, the left end of the guide tube has a step (Figs. 2b and 3), a segment with a larger diameter, to prevent leftward motion of the Hoek cell. The length of the rear supporter (10 mm as shown in Fig. 2a) is much shorter than that of the guide tube in contact with the membrane (83.5 mm) (Fig. 2c). The purpose of this design is to minimize the contact area of the rear supporter with the membrane: during the dynamic tests, the specimen

and the rear supporter slide rightwards (Fig. 3), and the smaller contact area between the rear supporter and the membrane leads to smaller friction force, therefore reducing the measurement error. This will be verified by the dynamic force balance shown in Section 3.2.2.

Strain gauges were glued at symmetrical positions on the incident bar and the transmitted bar. The incident strain wave ε_i and reflected strain wave ε_r are measured by the strain gauge on the incident bar, the transmitted strain wave ε_t is measured by the strain gauge on the transmitted bar. All the strain gauge signals are transmitted to an eight-channel Sigma digital oscilloscope through a signal conditioner and Wheatstone bridge. Based on these waves, the loading history of the specimens can be calculated.

Ideally, when the Hoek cell is pressurized, constant pressure will be applied on the side surface of the guide tube, the disc specimen and the rear supporter. However due to the material mismatch between the rock and the steel, the membrane will squeeze into the interface between the rock and the steel, thus separating the specimen assembly. To ensure the specimen assembly remains intact in the Hoek cell while maintaining accurate measurement of the dynamic load, the SHPB system is modified to apply axial pre-stress in the current study (Fig. 3).

This design is similar to that presented in our early work to examine the effect of various static stress states on the dynamic responses of rocks (Wu et al. 2015; Wu et al. 2016), where two pressure chambers are fixed onto the supporting platform of the SHPB system through two reaction plates connected by tie-rods. In the current design, the rear pressure chamber remains while the front pressure chamber is replaced by the Hoek cell. The pre-stress is applied by pressurizing the rear pressure chamber attached to the right end of the transmitted bar (Top insert in Fig. 3). This stress stops the rightward motion of the transmitted bar and thus the specimen assembly. The leftward motion of the Hoek cell is prevented by the left reaction plate through the step of the guide tube. There is a hole on the left reaction plate, allowing the incident bar to go through. Also, because the diameter of the incident bar is slightly smaller than the inner diameter of the guide tube (Fig. 2), it can move freely. At the same time, the specimen assembly remains intact inside the Hoek cell even under high confining pressure.

Table 1 Summary of the physical and mechanical properties of bars

Young's modulus, E	Density, ρ	P-wave velocity, c	Yield strength
200 GPa	8100 kg/m ³	5020 m/s	2.5 GPa

2.3 Force analysis of the PS assembly

Because of the modification and the application of the axial pre-stress, the forces applied on the specimen have to be carefully analyzed for the purpose of data reduction. According to the stress wave theory, the loading forces P_1 and P_2 on the two ends of the PS specimen assembly due to stress waves can be calculated as (Kolsky 1949):

$$P_1 = AE(\varepsilon_i + \varepsilon_r) \quad (1)$$

$$P_2 = AE\varepsilon_t \quad (2)$$

where A and E are the cross-sectional area and Young's modulus of the bars, respectively.

Fig. 4 Analysis of the forces on the PS specimen assembly.

In the current design, the free body diagram of the PS specimen assembly (Fig. 4) shows that the total force on the right end (F_1) and total force on the left end (F_2) are:

$$F_1 = P_1 \quad (3)$$

$$F_2 = P_2 + A\sigma_{pre} \quad (4)$$

It is generally accepted that if the dynamic tests is under the dynamic force equilibrium condition (i.e., $F_1 = F_2$ assuming friction is negligible, which will be proven in Section 3.2.2),

the inertial effect in the dynamic tests can be ignored (Xia and Yao 2015; Zhang and Zhao 2014; Zhou et al. 2012). In this work, the pulse-shaping technique is used to achieve the force equilibrium. Under such conditions, the dynamic punch shear stress in the specimen can be calculated using the following equation (Huang et al. 2011):

$$\tau(t) = \frac{F(t)}{\pi DB} \quad (5)$$

where $\tau(t)$ is the punch shear stress; $F(t) = F_1 = F_2$ is the loading force; D and B are the diameter of the incident bar and the thickness of the specimen, respectively. The shear strength τ_s is the shear stress corresponding to the failure load.

As shown in Fig. 2c, when the Hoek cell is pressurized, the lateral pressure is applied on the side surface of the specimen, thus the value of the pressure on this surface can be directly obtained by the pressure gauge. According to the elastic theory, when a cylinder is under lateral uniform pressure (p_0), inside the cylinder the radial stress is equal to the pressure p_0 regardless of the radius (Lemaitre and Chaboche 1994). Hence in the current study, the normal stress of the shearing surface (σ_{nor}) is equal to p_0 , which is the pump pressure measured by the pressure gauge disregarding losses in the connections, which are assumed to be negligible (Fig. 3).

3 Applications to Green Sandstone

3.1 Specimen preparation

In this study, the rock specimens are made of green sandstone (GS), one of the carving sandstone in Dazu County of Sichuan Province, China. It is found in a stratum under the Peng-laizhen group of the late Jurassic. The specimen was scanned by the electron probe microanalyzer (EPM), and the mineral map is shown in Fig.5. The results show that the mineral grain size of GS ranges from 10 μm to 200 μm with an average quartz size of 150 μm and an average feldspar size of 200 μm . Quartz is the dominant mineral with 30.4%, followed by plagioclase and ferromagnesian oxide. The mineralogical composition of GS is summarized in Table 2. The physical and mechanical properties of GS are measured following

the corresponding ISRM suggested methods (Ulusay 2014) and are summarized in Table 3 .

Fig. 5 Mineral map of GS.

Table 2 Mineral composition of green sandstone

Mineral composition	Content (%)
Quartz	30.4
Plagioclase	27.17
Fe_Mg_Oxide	12.15
K-Feldspar	10.31
Rutile	3.14
Ca(OH) ₂	2.88
Sphene	1.1
Calcite	0.85
Ilmenite	0.72
Rests	11.28

Table 3 Summary of the physical and mechanical properties of green sandstone

Density	P-wave velocity	Uniaxial Compressive strength	Brazilian tensile strength	Young's modulus	Poisson's ratio
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2330 kg/m ³	3500 m/s	40 MPa	5.4 MPa	8.5 GPa	0.30
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3.2 Validation of loading conditions

3.2.1 Dynamic force balance for tests without confinement

It is noteworthy that the prerequisite for using static punch shear Eq. (5) for stress analysis is the elimination of the inertial effect in the specimen during the dynamic test (Huang et al. 2011). Similar to the other SHPB dynamic tests on brittle materials, the pulse-shaping technique was applied in the current study to achieve the dynamic force balance and thus the elimination of the axial inertial effect (Chen et al. 1999). A C1100 copper disc (8.4 mm in diameter and 1.0 mm in thickness) was chosen as the pulse shaper to modify the incident wave from a rectangular shape with oscillation to a smooth sinusoidal shape, which is necessary to achieve the dynamic force balance in the specimen (Dai et al. 2010; Zhang and Zhao 2014). The dynamic force balance for the typical punch shear test without confinement is shown in Fig. 6a. The total forces on the two ends of the specimen F_1 and F_2 in Fig. 6 were calculated by Eq. (3) and (4). It can be seen from the figure that F_1 and F_2 are almost identical near the peak, indicating that the force balance is achieved and the static Eq. (5) is applicable to analyze the dynamic shear stress.

3.2.2 Dynamic force balance for tests with confinement

For PS tests with confinement, due to the application of the lateral confinement, friction between the specimen and the membrane will exist and have an effect on the dynamic force balance, as well as on the shear stress measurement results. Below, we will consider the friction in the assessment of the dynamic force balance.

Following the common technique to achieve the dynamic force balance in SHPB tests (Xia and Yao 2015; Zhang and Zhao 2014; Zhou et al. 2012), the pulse shaper technique is adopted. In the current study, a C1100 copper disc, 8.4 mm in diameter and 1.4 mm in thickness was chosen as the pulse shaper to modify the incident waves. These dimensions were determined by trial-and-error to achieve incident waves with the desired shape. The typical dynamic loading force with confinement of 20 MPa is shown in Fig. 6b. It is obvious

that F_1 and F_2 are nearly identical up to the peak. As seen in Fig. 4, the equilibrium condition of the PS sample assembly reads $F_1 = P_1 = F_2 + f$, where f is the friction acting on the PS specimen assembly. Therefore the balance between F_1 and F_2 proves that the punch shear design successfully minimizes the friction between the specimen and the membrane. Another noticeable difference between the two subfigures in Fig. 6 is that before the arrival of the stress waves, P_2 has a finite value when there is a pre-stress (Fig. 6b) while P_2 is zero before the arrival of the stress wave when there is no confinement (Fig. 6a). This difference is caused by the initial axial pre-stress applied to ensure the intactness of the specimen assembly when there is confinement as described in Section 2.2 and theoretically explained in Section 2.3. For the confinement level of 20 MPa, the axial pre-stress was set at 9 MPa.

Fig. 6 Dynamic force balance checks for typical dynamic punch shear tests with pulse-shaping (a) Loading rate of 800 GPa/s and confinement of 0 MPa, (b) Loading rate of 2420 GPa/s and confinement of 20 MPa.

3.2.3 Determination of the loading rate and characteristics of the loading curves

After the dynamic force balance, the dynamic punch shear stress in the specimen can be calculated by Eq. (5), and the typical shear stress histories are shown in Fig. 7. Fig. 7a shows the dynamic shear stress history without confinement, and Fig. 7b the typical shear stress with confinement of 20 MPa. It is worth noting that, both figures show obvious peak points, corresponding to the dynamic punch shear strength and the onset of shear failure. According to the suggested method for the determination of the dynamic loading rate, the loading rate of

the PS test is determined as the slope of the shear stress history before the failure onset (Zhou et al. 2012). In these two typical cases, the loading rate for the PS tests is denoted by $\dot{\tau}$, and the values are given in the figure.

In addition, the characteristics of the shear stress-time curve in Figs. 7a and 7b are apparently different: the post-peak of the stress drops to a plateau superimposed with oscillation in Fig. 7b, while in Fig. 7a the shear stress drops to zero. The shear failure occurs at the peak of the shear stress, resulting in an inner rock plug and an outer rock ring that are in contact. Because the specimen (Fig. 7b) is still under the uniform lateral compression, the further relative motion between the inner rock plug and the outer rock ring causes dynamic friction. The residual shear stress in the confined PS tests balances this dynamic friction. The further decrease of the shear stress after time 250 μs is due to unloading of the stress pulse (Fig. 7b).

Fig. 7 Typical shear stress-time curves for determining the loading rates (a) confinement of 0 MPa; (b) confinement of 20 MPa.

3.3 Failure mode of the PS specimen

The failure mode of the specimen is a visual indicator of the failure mechanism of rocks (Patton 1966). In this study, the compressive axial load produces a cylindrical shear failure surface, and the specimens are split into a rock ring and a rock plug. To recover the rock ring, the side surface of the specimen is wrapped with black electric tape (Fig. 8b). Using the specially designed rear supporter, the rock plug is also recovered. The recovery of the rock ring and rock plugs is thus accomplished as shown in Fig. 8. Several radial cracks can be

found on the rings in Figs. 8a and 8c. In order to examine the damage of the recovered specimen due to only the dynamic loading, the rock plug was left in the rock ring (Fig. 8b).

Fig. 8 Photographs of PS specimens. (a) Front view of typical specimen before and after the dynamic PS test; (b) side view of typical specimen before and after the dynamic PS test; (c) typical rock ring and rock plug produced by the dynamic PS test.

Although the main fractures are visible, internal cracks within the PS specimens after the dynamic loading are not. Furthermore, the shear failure surface of the tested specimen is only partially visible (Fig. 8b). The X-ray micro CT technique was thus utilized to investigate the cracks and the shear failure surfaces inside the recovered rock specimens. The tested PS specimens were scanned by the nanoVoxel 2102E micro CT system by Sanying Precision Instruments at 150 kV and 60 μ A with an exposure time of 1.6 seconds. During the scanning, the axis of the specimen was positioned perpendicularly to the scanning direction.

In this study, three groups of GS specimens were dynamically tested with lateral confinements of 0, 10 and 20 MPa. For the confinement of 10 MPa, the axial pre-stress is 4.5 MPa and for the confinement of 20 MPa, the axial pre-stress is 9 MPa. The CT images of the recovered specimens with different lateral confinements and loading rates are shown in Fig. 9. The cracks shown as black lines, while the grey and white areas are the different minerals. There are several cracks in the rock ring as seen in Fig.9. Fig. 9a shows the specimen tested under quasi-static condition, for comparison purposes. The methodology for the quasi-static test was described in Section 2.2 and the velocity of the load platen was set as 0.002 mm/s. Figs. 9b and 9c show the specimens tested under the loading rates of 800 GPa/s and 1500 GPa/s without confinement. The specimens in the second row of Fig. 9 (i.e., d, e, f) are tested under the loading rates of 1450 GPa/s, 2000 GPa/s and 2550 GPa/s respectively while being

subjected to the confinement of 10 MPa. Tested under roughly the same loading rates as those in the second row, the specimens in the third row of Fig. 9 (i.e., g, h, i) are subjected to the confinement of 20 MPa. One can see from the figure that the number of cracks in the rock rings increase with the loading rate and decreases with the increase of the confinement.

Fig. 9 CT images of PS specimens under various loading conditions. Zero confinement pressure with (a) quasi-static, (b) loading rate of 800 GPa/s, (c) loading rate of 1500 GPa/s; 10 MPa confinement with loading rate of (d) 1450 GPa/s, (e) 2000 GPa/s, (f) 2550 GPa/s; 20 MPa confinement with loading rate of (g) 1400 GPa/s, (h) 1900 GPa/s, (i) 2420 GPa/s.

3.4 Effects of the loading rate and the normal stress on the shear strength

It is generally accepted that when the dynamic force balance is achieved in dynamic tests, the peak loading force is attained near the failure time of the specimen (Zhou et al. 2012). This principle has been applied in PS tests (Huang et al. 2011; Yao et al. 2017). The dynamic

punch shear strength of the specimen can be calculated from the peak load by using Eq. (5), while the normal stress is the same as the lateral confinement exerted by the Hoek cell (Lemaitre and Chaboche 1994).

For comparison purposes, static tests with the same confinements were conducted. Fig. 10 illustrates the relation between the shear strength and the loading rate under different normal stresses. It can be observed that the shear strength with a given confinement increases almost linearly with the loading rate, which is similar to the results reported in Xu and Dai (2018). An additional conclusion from the figure is that at a given loading rate, the shear strength increases with the normal stress due to confinement. For a given confinement, a straight line is fitted to the shear strength data using the least squares method as shown in Fig. 10.

Fig. 10 Dynamic punch shear strength under different loading rates and confining pressure (i.e., normal stress) and data fitting of the results.

4 Data Interpretation within the theoretical framework of the Coulomb criterion

The Coulomb criterion is the simplest and most widely used strength criterion in rock mechanics. According to the Coulomb criterion, the static shear strength along the shear plane is:

$$\tau_s = C_0 + \mu \sigma_{\text{nor}} \quad (6)$$

Under dynamic loading conditions, the classic Coulomb formula can be extended as:

$$\tau_s(\dot{\tau}) = C_0(\dot{\tau}) + \mu(\dot{\tau}) \sigma_{\text{nor}} \quad (7)$$

where $\dot{\tau}$ is the loading rate. In general, the shear strength, the cohesion and the coefficient of friction are all rate dependent, the normal stress is however constant in the current study.

When the normal stress is zero in the equation, the dynamic punch shear strength equals the dynamic cohesion $C_0(\dot{\tau})$. As shown in Fig. 10, the shear strength without confinement (i.e., cohesion) is clearly rate dependent. This rate dependence phenomenon has also been reported for the cohesion of other rocks (Huang et al. 2011; Yao et al. 2017) and other mechanical properties of rocks such as compressive strength, tensile strength, and fracture toughness (Zhang and Zhao 2014).

When the confining pressure is applied on the specimen, the shear strength is further increased. Comparing the three sets of dynamic punch shear strengths shown in Fig. 10, the fitting curves of the shear strength are approximately parallel with roughly identical distance. This implies that the term of $\mu(\dot{\tau}) \sigma_{\text{nor}}$ in Eq. (7) only depends on the normal stress, and it is roughly independent of the loading rate. Because σ_{nor} is rate independent, therefore $\mu(\dot{\tau})$ is independent of the loading rate, too.

Based on the relations between the rock shear strength and the loading rate, and between the shear strength and the normal stress, an empirical equation based on the Coulomb theory is proposed to describe the rock shear strength:

$$\tau_s = C_0 + \alpha \frac{\dot{\tau}}{\dot{\tau}_0} + \sigma_{\text{nor}} \tan \phi \quad (8)$$

where C_0 (=19.30 MPa) is the cohesion that is measured as the mean static PS strength of the rock material without normal stress, $\dot{\tau}_0$ (=1 GPa/s) is the reference loading rate, ϕ is the internal friction angle, and α is a fitting parameter. When σ_{nor} is zero, Eq. (8) is reduced to $\tau_s = C_0 + \alpha \frac{\dot{\tau}}{\dot{\tau}_0}$, which describes the dependence of the cohesion on the loading rate.

Fitting the entire data set of the dynamic shear strength using Eq. (8), we obtain the

average value of $\alpha = 0.015$ and internal friction angle $\phi = 49^\circ$, which is within the range of the internal friction angles for sandstones (Jaeger 1979).

In summary, the rate dependence of cohesion of GS observed in this work is similar to the rate dependence of other rock mechanical properties as summarized by Zhang and Zhao (2014). However, the internal friction angle seems to be rate independent. These observations are consistent with those made by Zhao and his coworkers (Li et al. 2000; Li et al. 1999; Zhao 2000) for a different rock type.

5 Conclusions

A 25.4 mm diameter split Hopkinson pressure bar was modified to systematically investigate the dynamic punch shear strength of green sandstone under different lateral confinements using a 1.5 inch Hoek cell. The axial pre-stress was utilized in the modified split Hopkinson pressure bar system to ensure that punch shear specimen assembly remained intact when the lateral confinement was applied. The dynamic force balance during dynamic punch shear tests was critically assessed. Three groups of green sandstone specimens were statically and dynamically tested under the lateral confining pressures of 0, 10 and 20 MPa and loading rates up to 3000 GPa/s. The experimental results were analyzed within the theoretical framework of the Coulomb failure criterion.

The results showed that the dynamic punch shear strength increases with the loading rate and the normal stress. In addition, the cohesion is significantly enhanced with the increase of the loading rate. This rate dependence of cohesion is in accordance with the rate dependency of mechanical properties for many engineering materials. However, the internal friction angle is approximately independent of the loading rate under the experimental conditions used in this study. This conclusion is consistent with that reached by Zhao and his coworkers for Bukit Timah granite using dynamic triaxial tests. It is noted that the conclusion may be rock type dependent and should be applied with caution. For other rock types, more investigations are needed.

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Figure Captions

Fig. 1 Different types of punch tests: (a) punch shear (PS) test, (b) punch through shear (PTS) test, (c) block punch test.

Fig. 2 Schematic of the punch shear specimen assembly with lateral confinement: (a) the punch shear specimen assembly; (b) the guide tube; (c) the Hoek cell enclosing the punch shear specimen.

Fig. 3 Schematics of the modified SHPB system with the Hoek cell enclosing the PS specimen assembly. The top insert shows the operational mechanism of the system.

Fig. 4 Analysis of the forces on the PS specimen assembly.

Fig. 5 Mineral map of the GS.

Fig. 6 Dynamic force balance for a typical dynamic punch shear test with pulse-shaping (a) Loading rate of 800 GPa/s, confinement of 0 MPa, (b) Loading rate of 2420 GPa/s, confinement of 20MPa.

Fig. 7 The typical shear stress-time curve for determining the loading rate (a) confinement of 0 MPa; (b) confinement of 20 MPa.

Fig. 8 Photographs of PS specimens. (a) Front view of typical specimen before and after the dynamic PS test; (b) side view of typical specimen before and after the dynamic PS test; (c) typical rock ring and rock plug produced by the dynamic PS test.

Fig. 9 CT images of PS specimens under various loading conditions. Zero confinement pressure with (a) quasi-static, (b) loading rate of 800 GPa/s, (c) loading rate of 1500 GPa/s; 10 MPa confinement with loading rate of (d) 1450 GPa/s, (e) 2000 GPa/s, (f) 2550 GPa/s; 20 MPa confinement with loading rate of (g) 1400 GPa/s, (h) 1900 GPa/s, (i) 2420 GPa/s.

Fig. 10 Dynamic punch shear strength under different loading rates and confining pressure (i.e., normal stress) and data fitting of the results.