The dynamic tensile strength and failure characteristics of transversely isotropic shale under impact Brazilian test

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ABSTRACT: To comprehensively understand the failure behaviors under dynamic loading, a series of SHPB tests are conducted on deep Longmaxi shale under different loading rate at seven loading-bedding angles β. The results indicate that both static and dynamic BTS increase with the angle β. But the dynamic BTS are far greater than the static. However, as the loading rate increases, the anisotropic index decreases gradually. There is a positive correlation between dynamic BTS and loading rate, which is that the dynamic BTS increases with loading rate and the relation between dynamic BTS and loading rate is fitted by a power function with correlation coefficients R^2 higher than 0.92. The failure results show that there are four typical fracture patterns, which are central tensile failure as β=0° and β=90°, bedding activation shear failure as β=15°, non-central arc fracture at β=30° and 45°, mixed mode fracture as β=60° and 75°, respectively.

Keywords: Longmaxi shale, transversely isotropic, split Hopkinson pressure bar (SHPB), dynamic Brazilian tensile strength (BTS), failure patterns.

1 INTRODUCTION

In recent years, development of shale gas has been booming in Sichuan Basin of China, where the major target play is the Longmaxi shale (Zou et al. 2021). As a typical sedimentary rock, Longmaxi shale shows anisotropy in nature due to the bedding planes and laminations which consequently affects the mechanical behaviour (Jia et al. 2017). Among these mechanical properties, the tensile strength and failure is vital for analysis of borehole instability in horizontal drilling. Up to now, there are many investigations to study the static tensile strength of shale from the Brazilian test because of its simple specimen preparation and experimental set-up (Aliabadian et al. 2017). However, shale may bear dynamic loading during drilling, such as the impact of drill string vibration on the borehole wall. This might induce dynamic tensile failure of shale, which needs to be in-depth investigation.

To study the dynamic tensile mechanical properties of rock under impact loading, the Brazilian disk (BD) under split Hopkinson pressure bar (SHPB) is an effectively method. The dynamic behaviour of different kinds of rocks have been reported, such as Laurentian granite (Wu et al. 2015). To measure the effect of bedding planes on failure characteristics and anisotropic tensile strength of layered rocks, some SHPB tests have been conducted on coal, phyllite, slate and shale (Qiu et al. 2017, Liu et al. 2020, Yang et al. 2020 and Shi et al. 2022). Ai et al. (2020) investigated crack propagation and dynamic properties of coal with vertical and horizontal beddings under SHPB impact loading, which showed that bedding directions have a major influence on dynamic tensile strength and crack propagation path. Guo et al. (2022) carried out a series of SHPB tests of shale with 5 different bedding orientations (0◦, 30◦, 45◦, 60◦ and 90◦), which found that the dynamic tensile strength of shale increases with loading rate and the main failure is classified into tensile, shear and tensile-shear failure.

Although the above experiments indicate that the bedding planes have a great influence on the mechanical properties of shale, the anisotropic dynamic tensile strength, fracture propagation and failure patterns of Longmaxi shale are still rare at present. The objective of this paper is to study the dynamic Brazilian tensile strength (BTS) and failure characteristics of Longmaxi shale under different loading rate at seven loading-bedding angles β from 0° (loading direction parallel to bedding) to 90° (loading direction perpendicular to bedding) at 15° intervals by SHPB tests. The obtained results will be useful for understanding the nature properties of shale and for safe drilling in shale gas development.

2 EXPERIMENTAL METHODS

2.1 Samples preparation

Shale samples in this study are collected from a black shale outcrop in the Lower Silurian deep Longmaxi Formation. The Brazilian disk (BD) samples with 50mm in diameters and 25mm in thickness are drilled along the bedding plane. To study the effect of layered bedding on dynamic tensile failure, seven angles between loading direction and the bedding are considered, which are β=0°, 15°, 30°, 45°, 60°, 75°, and 90°, respectively (Figure 1).

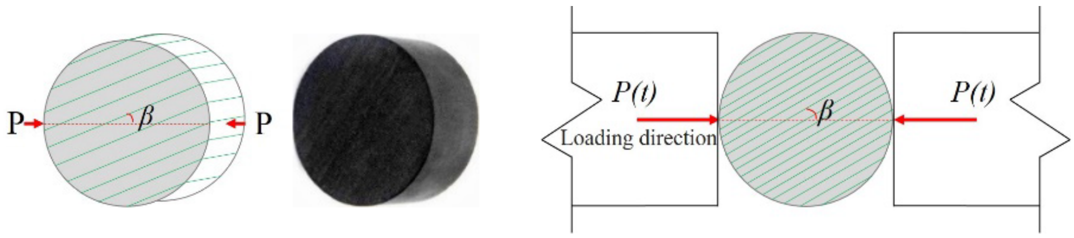


Figure 1. The samples and loading diagram (β is the angle between loading direction and bedding).

By using XRD analysis and other basic mechanical tests, the mineralogy, density, porosity, permeability of this shale are measured, respectively. The composition of Longmaxi shale is mainly composed of 56.25% quartz, 7.54% plagioclase, 4.18% calcite, 10.62% dolomite, 18.26% clay minerals and 3.15% Pyrite. The average bulk density of this shale is 2.723g/cm^3, the porosity of the samples ranges from 3.93% to 5.14%, the permeability varies from 2.92 × 10^{-10} to 1.071 × 10^{-6} mD, and the average TOC is 3.46%.

2.2 Experimental Procedure

The impact Brazilian test is conducted on a SHPB system (Figure 2), which includes a gas gun, a spindle-shaped striker, an incident bar, a transmission bar, and data acquisition system (Qiu et al. 2017, Liu et al. 2020, Wu et al. 2021 and Shi et al. 2022). The striker, incident bar and transmission bar are made from alloy steel with 50 mm in diameter, and the density, Young's modulus and P-wave velocity are 7810 kg/m^3, 240 GPa and 5150 m/s, respectively. During the test, the shale disk sample is diametrically clamped between the incident bar and the transmission bar. The gas pressure in gas gun is set to 0.5 MPa, which drives the striker impacting the incident bar to generate a compressive stress wave and reflective tensile stress wave in incident bar and a transmission compressive stress wave in transmission bar (Liu et al. 2020 and Guo et al. 2022). Finally, the stress at both ends of the disk are obtained from one-dimensional wave theory. The dynamic loading can be usually characterized by the loading rate, which is the slope of the stress-strain curve before the failure point.

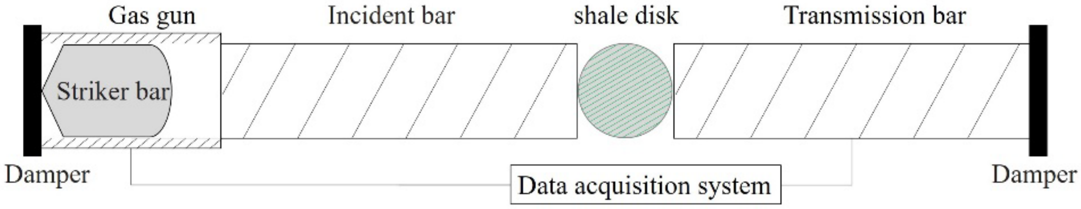


Figure 2. The schematics of split Hopkinson pressure bar (SHPB) system.

When the loading force on two ends of shale disk reaches equilibrium and the peak value, the dynamic tensile strength can be determined. For transversely isotropic rocks, Claesson and Bohloli (2002) deduced an explicit analytical solution of Brazilian tensile strength (BTS) as follow:

$$\sigma_{td} = \frac{2P_{max}}{\pi D t}\left[\left(\frac{E}{E'}\right)^{\cos(2\beta)/4} - \frac{\cos(4\beta)}{4}(b-1)\right] \tag{1}$$

$$b = \frac{\sqrt{EE'}}{2}\left(\frac{1}{G'} - \frac{2v'}{E'}\right) \tag{2}$$

where E is the Young's modulus parallel to the bedding plane, GPa. E' and G' are the Young's modulus and shear modulus perpendicular to the bedding plane, respectively, GPa. And v' is Poisson's ratio perpendicular to the bedding plane. Parameters E, E' and v' are determined by uniaxial compression tests where the loading direction is parallel to and perpendicular to the bedding plane, which are E=35.87GPa, E'=29.73GPa and v'=0.26, respectively. While the shear modulus G' is calculated according to:

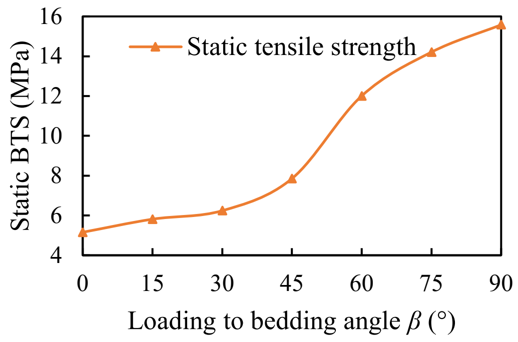
$$\frac{1}{G'} = \frac{1}{E} + \frac{1}{E'} + \frac{2v'}{E'} \tag{3}$$

3 EXPERIMENTAL RESULTS AND DISCUSSION

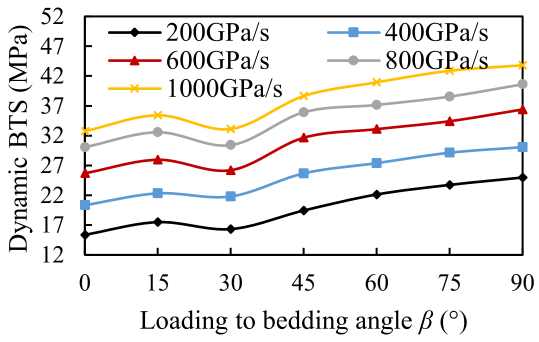
3.1 Effect of bedding planes on tensile strength

Figure 3 shows the static and dynamic Brazilian tensile strength (BTS) under different loading direction to bedding angle β. As can be seen, whether static or dynamic BTS of deep Longmaxi shale has obvious anisotropy, which varies with angle β. For static BTS in Figure 3(a), it increases with the angle β increasing from 0° to 90°. And the minimal static BTS is at β=0° with a value 5.157MPa, while the maximal BTS is 15.578MPa at β=90°. Figure 3(b) illustrates the dynamic BTS changes with the angle β under 5 different loading rate. At a certain loading rate, dynamic BTS shows an ascend-slightly decline-ascend trend with increasing of angle β. The dynamic BTS firstly increases at β=0° to 15°, then decreases slightly at 15° to 30°, and then increases gradually at 30° to 90°. Similarly, the minimal dynamic BTS is at β=0° while β=90° has a maximal value for different loading rate. Moreover, the dynamic BTS increases with the loading rate under a certain angle β. There is a positive correlation between the dynamic BTS and loading rate.

To quantitatively evaluate the anisotropy of the dynamic BTS of Longmaxi shale, the anisotropic index are obtained via the method suggested by Shi et al. (2018) and Liu et al. (2020), which is defined as the ratio of the maximum to the minimum of BTS at a same loading rate. Figure 4 shows the variation of anisotropic index versus the loading rate.



(a) Static BTS



(b) Dynamic BTS

Figure 3. The relationship between experimental and predicted BTS and loading-bedding angle.

According to the results, the anisotropic index of the static loading is 3.021, showing a strong anisotropy in static tensile strength, which is much higher than that of dynamic loading. Moreover, the anisotropic index decreases gradually with the increase of loading rate, which indicates that the impact loading would weaken the bedding anisotropy effect on dynamic BTS.

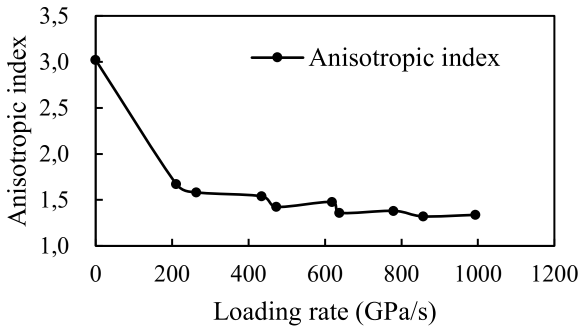


Figure 4. The variation of the anisotropic index with loading rate.

3.2 *Effect of loading rate on tensile strength*

The relationships between the dynamic BTS and loading rate under different loading direction to bedding angle β are shown in Figure 5. What can be seen from the results is that the dynamic BTS increases with increasing of loading rate under seven bedding angle, respectively. This indicates that there is obvious loading rate effect in deep Longmaxi shale under impact Brazilian test. Meanwhile, when β increases, the dynamic BTS gradually increases from minimum at 0° to maximum at 90°, which is consistent with the results under static conditions.

According to previous studies, the dynamic BTS showed a power function relation with the loading rate (Wu et al. 2015, Liu et al. 2020 and Guo et al. 2022). Based on the results as shown in Figure 5, the dynamic BTS and loading rate fitting formulas of deep Longmaxi shale are obtained and listed in figure, the general formula is as following:

$$\sigma_d = \sigma_s + A\tau^B \quad (4)$$

Where, σ_d and σ_s are the dynamic and static BTS, respectively, τ is the loading rate, A and B are fitting parameters. The second term represents the rate dependence effect in this equation, which shows that if there is no dynamic loading, the result is the static BTS (Wu et al. 2015). In this study, the correlation coefficients R^2 of all fitting curves are higher than 0.92, which is sufficient to indicate that the dynamic BTS of deep Longmaxi shale has a good power relationship with the loading rate.

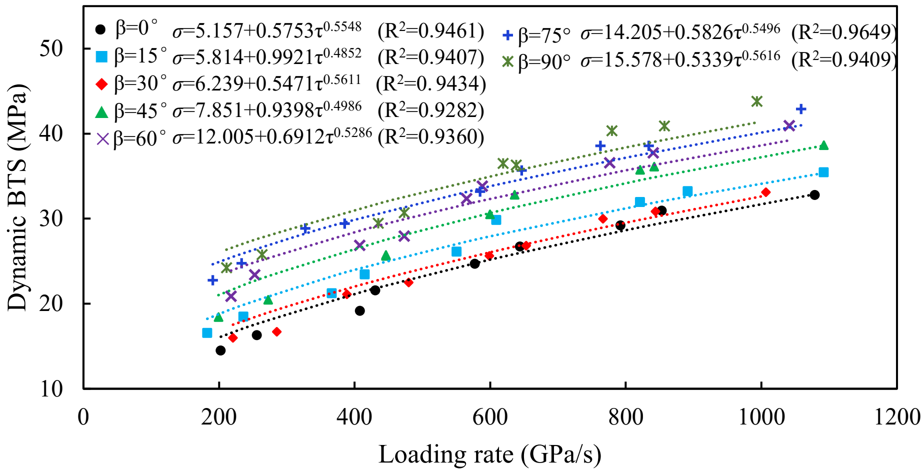
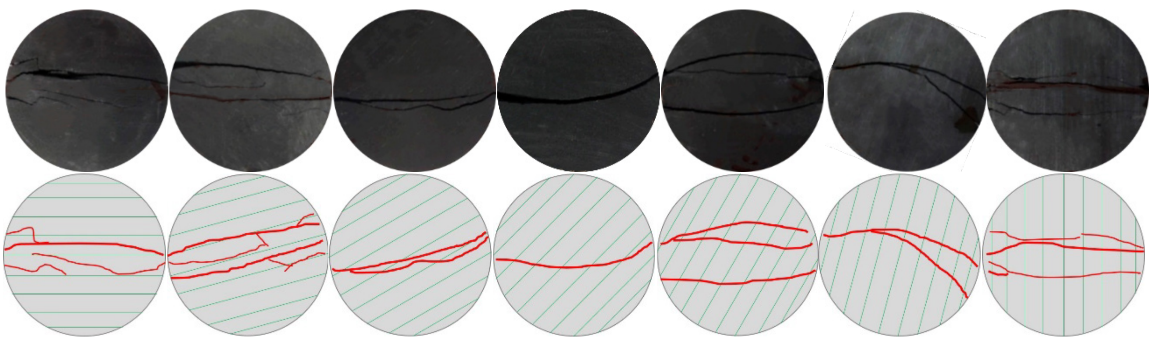


Figure 5. The dynamic BTS versus loading rate for different loading-bedding angle.

3.3 *Failure patterns and characterization*

The static Brazilian test shows that the bedding plane orientation has an obvious influence on the failure types and fracture morphology, which can be divided into tensile failure, shear failure, and mixed tensile and shear failure for transversely isotropic rocks (Liu et al. 2020). As to the impact SHPB test, the loading rate is another important factor affecting the dynamic failure characteristics of shale. Figure 6 plots the fracture morphology of shale discs with loading-bedding angle of 0°, 15°, 30°, 45°, 60°, 75° and 90° at loading rate of 400 GPa/s under dynamic test. Compared with the static failure of a single main fracture (Dan et al. 2013 and Wang et al. 2017), there are multiple main fractures and secondary fractures along the bedding plane or loading direction, forming a complex fracture network under impact loading.

According to the fracture morphology of deep shale discs after SHPB test, the failure mode varies with the orientation of the bedding plane. As β=0°, there is a group of parallel fractures along the loading direction and central bedding planes and the fracture mode is pure tensile failure along beddings. As β=15°, there is also a group of parallel fractures along the beddings but off-centre, which are shear slippage along the beddings. When β=30° and 45°, a mixture of shear and tensile failure coexists and the fractures are off-center with curve lines. A group of approximately parallel curve fractures along the loading direction occurs at β=60° with a mixed-mode failure including tensile splitting and shear failure. When β=75°, shale disc mainly exhibits off-centre curve fracture accompanied by branched fracture, which is also a mixed-mode failure. The parallel fractures along the loading direction at β=90° are perpendicular to the bedding plane, which is pure tensile failure of rock matrix and propagates through bedding planes. In this case, the shale matrix controls the tensile strength, which is the highest BTS.



(a) β=0° (b) β=15° (c) β=30° (d) β=45° (e) β=60° (f) β=75° (g) β=90°

Figure 6. The typical failure patterns of deep shale discs at 400 GPa/s under impact Brazilian test.

4 CONCLUSIONS

In this study, a thorough investigation of the dynamic tensile strength and failure characteristics of deep Longmaxi shale is carried out by using SHPB test. The disk-shaped samples with seven loading direction-bedding angles are considered, which are β=0°, 15°, 30°, 45°, 60°, 75°, and 90°, respectively. The following conclusions are drawn:

(1) For static and dynamic BTS, both increase with the bedding angle β increasing from 0° to 90°. But the dynamic BTS are far greater than the static at a given bedding angle. However, as the loading rate increases, the anisotropic index decreases gradually from 3.021 under the static loading to 1.337 under the dynamic loading.

(2) The dynamic BTS increases with the loading rate under a certain bedding angle β. There is a positive correlation between the dynamic BTS and loading rate. The relation between dynamic BTS and loading rate is fitted by a power function with correlation coefficients R^2 higher than 0.92.

(3) The failure results show that there are multiple main fractures and secondary fractures along the bedding plane and loading direction, forming a complex fracture network under impact loading. The typical fracture patterns are: pure tensile failure along loading as β=0° and β=90°, bedding activation shear failure as β=15°, non-central arc fracture at β=30° and 45°, mixed mode fracture as β=60° and 75°.

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