The tensile strength and failure characteristics of transversely isotropic deep Longmaxi shale under Brazilian test

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ABSTRACT: A series of Brazilian tests are conducted to investigate the anisotropic tensile failure of deep Longmaxi shale. The results indicate that the anisotropic Brazilian tensile strength (BTS) of deep shale shows an ascend-slightly decline-ascend trend with loading-bedding angle β. Five tensile failure criteria are used to predict BTS and compared with experimental results, the order of reliability is N-Z criterion > H-B criterion > L-P criterion > SPW criterion > MSPW criterion. Observing from failure of shale specimens, there are four typical fracture patterns: central straight fracture at β=0° and 90°, bedding activation shear failure fracture as β=15°, non-central arc fracture at β=30° and 45°, mixed mode fracture as β=60° and 75°. Moreover, there is an inverse relationship between BTS and bedding activation fracture. The cumulative AE counts-time curve exhibits a stepped increasing mode while AE counts show a monotonic decreasing trend with angle β.

Keywords: deep Longmaxi shale, transversely isotropic, Brazilian test, Brazilian tensile strength (BTS), failure patterns, AE characteristics.

1 INTRODUCTION

In China, the Longmaxi shale in Sichuan Basin is one of the most important target play for developing shale gas. As a typical sedimentary rock, Longmaxi shale shows inherently anisotropic behaviour due to the bedding planes and laminations (Jia et al. 2017). Anisotropy in tensile strength is vital for fracture pressure of drilling or breakdown pressure of hydraulic fracturing (Ma et al. 2017). Usually, the Brazilian test is broadly applied to obtain tensile strength because of its simple specimen preparation and experimental set-up (Ma et al. 2018 and Aliabadian et al. 2017).

Much work has been done by theoretical, experimental, and numerical methods for determining tensile strength of transversely isotropic rocks in Brazilian test. The angle β between the loading direction and bedding has a great effect on tensile strength (Dan et al. 2013, Vervoort et al. 2014, Mokhtari & Tutuncu 2016 and Zhang et al. 2018). Commonly, there are three types of failure patterns of transversely isotropic rocks under Brazilian test, which are central tensile failure along or across bedding, shear failure in lamination activation, and mixed-mode failure with tensile splitting and shear failure (Ma et al. 2018). To analyze the Brazilian failure process of transversely isotropic rocks, the SEM images, AE technique, strain measurement, high-speed photography and digital image correlation (DIC) etc. are utilized in Brazilian test (Wang et al. 2017, and Zhou et al. 2021). Meanwhile, the numerical methods, such as the UDEC, $FLAC^{3D}$, DEM-AE, PFC^{2D}/PFC^{3D}, were used as an aide to simulate the micro-level failure behavior and mechanism of failure under Brazilian test (Dan et al. 2013 and Tan et al. 2014).

The split fractures under Brazilian test do not always initiate and propagate at the disc centre, which means that the traditional isotropic elastic theory may not be suitable for transversely isotropic rocks. To calculate the accurate tensile strength, Claesson & Bohloli (2002) derived a reasonably formula for predicting tensile strength of transversely isotropic rocks. Moreover, in field of tensile failure criterion for anisotropic rocks, there are mainly five criteria: Hobbs-Barron (H-B) criterion, Nova-Zaninetti (N-Z) criterion, single plane of weakness (SPW) criterion, Lee-Pietruszczak (L-P) criterion and modified Single plane of weakness (MSPW) criterion (Ma et al. 2017). Among these criteria, the Nova-Zaninetti (N-Z) criterion is much suitable to characterize anisotropic tensile strength of layered rocks.

In this study, a series of Brazilian tests is conducted on shale disc specimens considering seven loading direction-bedding angles at β=0°, 15°, 30°, 45°, 60°, 75°, and 90°. Then, the typical anisotropic tensile failure criteria are evaluated to better capture the anisotropy of tensile strength. Thirdly, experimental results and failure mechanisms of this transversely isotropic shale is analysed from observing failure patterns and AE behavior. And some conclusions are finally obtained from this investigation.

2 TENSILE FAILURE CRITERIA FOR TRANSVERSELY ISOTROPIC ROCKS

For the anisotropic rocks, there are mainly five tensile failure criteria (Barron 1971, Nova & Zaninetti 1990, Lee & Pietruszczak 2015, Ma et al. 2017 and Gao 2020), which are listed as follows.

1. Hobbs-Barron (H-B) criterion

Based on Griffith crack theory, the Hobbs-Barron (H–B) criterion is defined as (Barron 1971):

$$\mathrm{T}(\beta) = \begin{cases} \dfrac{2T_0}{\cos\beta\,(1+\cos\beta)} & 0^\circ \le \beta \le \beta' \\ T_{90} & \beta' \le \beta \le 90^\circ \end{cases} \tag{1}$$

$$\cos\beta'\,(1+\cos\beta') = \frac{2T_0}{T_{90}} \tag{2}$$

where $T(\beta)$ is tensile strength as the loading to bedding angle is β, MPa; T_{90} and T_0 are tensile strengths of rock matrix and weakplanes, respectively. β' is the critical angle (°), where $T(\beta') = T_{90}$.

2. Nova-Zaninetti (N-Z) criterion

Nova-Zaninetti (N-Z) criterion for anisotropic tensile failure is (Nova & Zaninetti 1990):

$$\mathrm{T}(\beta) = \frac{T_0 T_{90}}{T_0\sin^2\beta + T_{90}\cos^2\beta} \tag{3}$$

3. Single plane of weakness (SPW) criterion

The SPW criterion is based on single plane of weakness theory (Lee & Pietruszczak 2015):

$$\mathrm{T}(\beta) = \begin{cases} \dfrac{T_0}{\cos^2\beta} & 0^\circ \le \beta \le \beta' \\ T_{90} & \beta' \le \beta \le 90^\circ \end{cases} \tag{4}$$

$$\beta' = \cos^{-1}\sqrt{\frac{T_0}{T_{90}}} \tag{5}$$

4. Lee-Pietruszczak (L-P) criterion

The L-P criterion for the transversely isotropic material is (Lee & Pietruszczak 2015):

$$\mathrm{T}(\beta) = \frac{T_0+T_{90}}{2} - \frac{T_{90}-T_0}{2}\cos 2\beta \tag{6}$$

5. Modified Single plane of weakness (MSPW) criterion

The modified the single plane of weakness criterion as follows (Gao 2020):

$$
\mathrm{T}(\beta) = \begin{cases} \dfrac{T_0}{\cos^2\beta} & 0^{\circ} \le \beta \le \beta' \\ \dfrac{T_{90}}{1 + 2\sin^2\beta\cos\beta} & \beta' \le \beta \le 90^{\circ} \end{cases} \tag{7}
$$

$$
\beta' = \tan^{-1}\left(\sqrt{\frac{T_{90}}{T_0}} - 1\right) \tag{8}
$$

3 EXPERIMENTAL METHODS AND RESULTS

3.1 Samples characterization and test procedure

Shale samples used in this research are collected from a black shale outcrop in the Lower Silurian deep Longmaxi Formation. The average bulk density of this shale is 2.723g/cm^3. The XRD analysis shows that the composition is 56.25% quartz, 7.54% plagioclase, 4.18% calcite, 10.62% dolomite, 18.26% clay minerals and 3.15% Pyrite.

The shale disc specimens are 50mm in diameters and 25mm in thickness. And the shale disk are categorized into two groups, Group-P and Group-V (Figure 1). For Group-P, the axis of the disc is parallel to the bedding, seven angles between the loading direction and bedding are considered, which are β=0°, 15°, 30°, 45°, 60°, 75°, and 90°, respectively. As for Group-V, the bedding planes are parallel to the disk faces. In the tests, four samples are tested for each angle β and Group-V.

(a) shale disk and loading of Group-P (b) shale disk and loading of Group-V

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

The Brazilian tests were conducted by using the RTR-1500 HTHP triaxial rock testing system with maximum loading capacity of 1500kN. A loading rate of 0.20 mm/min is used to ensure that the disk is under a quasi-static loading condition. The assumption of failure initiation at the disc center is basis for obtaining tensile strength under Brazilian test. Aliabadian et al. (2017) indicated that the failure may initiate at the disc centers for curved loading jaws with a larger load contact area. Hence, the curved jaws loading configuration is used here. And the AE sensor are used to record the AE characteristics of shale disk during testing.

3.2 Brazilian tensile strength and failure criteria assessment

Before calculation of BTS from the method of Claesson & Bohloli (2002), the Young's modulus and Poisson's ratio of parallel and perpendicular to bedding are obtained from uniaxial compression tests, which are 35.87MPa, 29.73MPa, 0.23 and 0.26, respectively. Then, the BTS of Group-P and Group-V shale specimens are obtained and the results of Group-P is plotted in Figure 2. It is observed that BTS of deep shale has obvious anisotropy, which shows an ascend-slightly decline-ascend trend with increase of loading-bedding angle β. And there is a sharp increase between 45° to 90°. The minimal BTS is at β=0° with average of 5.18MPa, representing tensile strength of bedding. While the average maximal BTS is 15.58MPa at β=90°, which is the tensile strength of the shale matrix.

Also, Figure 2 shows the predicted BTS values using different anisotropic tensile strength criteria. To some extent, all these criteria appear to be applicable for deep shale except MSPW criterion. To quantify the goodness-of-fit of these criteria, the three assessment indicators used in study of Ma et al. (2017) are employed here, which are the maximum absolute relative error (MARE), the average absolute relative error (AARE), and the standard error (SE). The lower values of MARE, AARE, and

SE indicate the higher goodness-of-fit of the criterion. From the results of Table 1, the reliability orders of these five failure criteria are as follows: N-Z criterion > H-B criterion > L-P criterion > SPW criterion > MSPW criterion. This indicates that the goodness-of-fit of N-Z criterion is much more reliable than other four criteria. Therefore, the N-Z criterion is recommended to describe the anisotropic tensile strength of the deep shale. However, whether this N-Z criterion is suitable for other layered rocks requires further experimental verification and investigation.

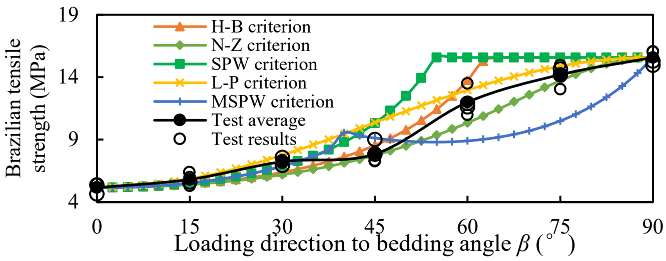


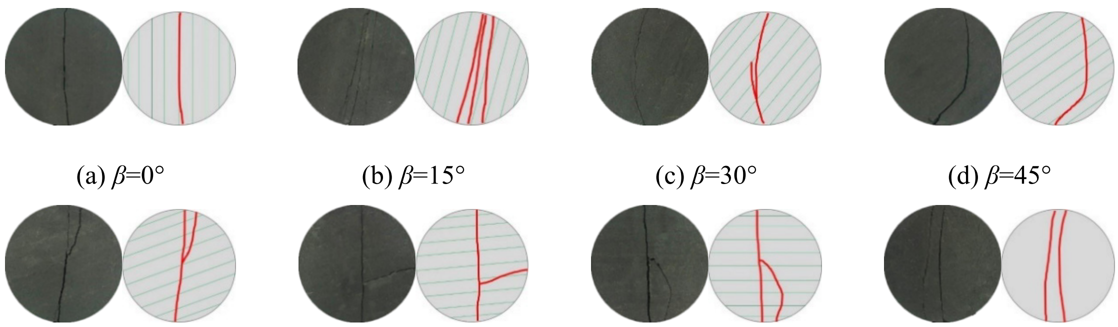
Figure 2. The relationship between experimental and predicted BTS and loading-bedding angle.

Table 1. Assessment indicators (MARE, AARE, and SE) of shale specimens with different diameters.

Indicators	Results of the assessment				
	H-B criterion	N-Z criterion	SPW criterion	L-P criterion	MSPW criterion
MARE	0.1462	0.1442	0.3144	0.3208	0.2604
AARE	0.0946	0.0777	0.1604	0.1215	0.1487
SE	0.9511	0.7772	1.7312	1.0705	1.8951

3.3 Failure patterns and characterization

Figure 3 shows failure patterns and schematics of deep shale at different loading-bedding angles β of Group-P and failure of Group-V, respectively. It's shown that the dominant fracture pattern for β=0° and 90° is a central tensile vertical fracture parallel to loading, which passes through the central point and goes through the upper and lower loading ends. The fracture at β=0° is along the bedding plane, while the fracture at β=90° is perpendicular to the bedding plane. Then fracture pattern turns gradually into shear failure along the bedding for β=15°, where the fractures also pass through the upper and lower loading ends but some of the fractures are not in the central part. When β=30° and 45°, shear failure mainly occurs and the fractures are off-center with curve lines. Similarly, a mixed-mode failure with tensile splitting and shear failure occurs at β=60° and 75°, but there is the through center fracture accompanied by branched fractures. For the Group-V, specimen fails by multiple fractures along loading direction accompanying layer activation.



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

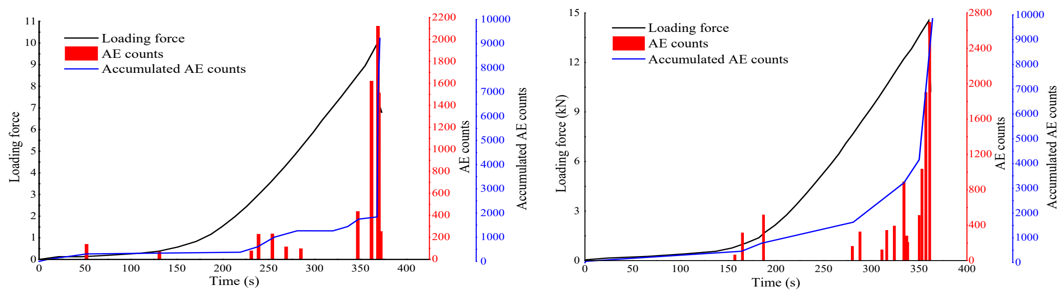
Figure 3. The typical fracture patterns of deep shale specimens under Brazilian test.

From Figure 3, tensile failure patterns of deep shale could be classified following four categories: (1) Type I, central straight line fracture, representing that shale occurs pure tensile failure, which are observed in Group-P at β=0° and 90° and Group-V specimens. (2) Type II, bedding activation shear failure fracture along bedding, which is mainly observed in Group-P at β=15°. (3) Type III, non-central arc fracture, which are observed in Group-P at β=30° and 45°. (4) Type IV, mixed mode fracture along and through the bedding plane, which are observed in Group-P at β=60° and 75°.

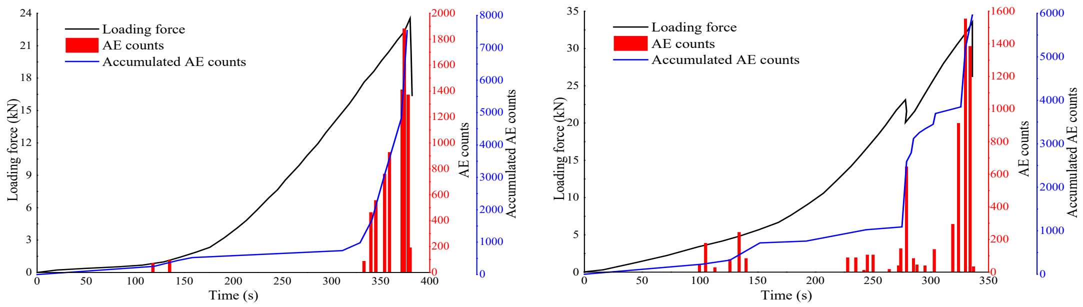
In fact, the BTS usually depends on the fracture modes. Vervoort et al. (2014) concluded that failure strength is inversely correlated with relative layer activation fracture length for layered sandstone. This means that lower strength has a higher layer activation fracture length. This is consistent with the results in this paper, where the bedding activation fracture decreases but the BTS increases gradually with angle β. For β=0° and 15°, the dominant fracture is bedding activation fracture induced by tensile and shear failure, which get lower BTS. As β=30° to 75°, the fracture patterns mainly are non-central arc fracture and mixed mode fracture, where fractures along bedding plane decrease and the BTS increases significantly. There are almost no bedding activation fractures at β=90° and the dominant failure is tensile splitting of shale matrix with highest BTS.

3.4 AE characteristics

The variation in AE counts, accumulated AE counts and loading force of different loading-bedding angle are presented in Figure 4. The stress-time curve can be divided into three stages, which is compaction stage with relatively rare AE counts, linear elastic deformation stage with sharply increasing AE counts, and failure stage with highest AE counts. In all, the AE counts are relatively few at a lower loading and sharply increase when the specimen suddenly breaks. The accumulated AE counts curves show a stepped increasing mode. Moreover, the AE counts are closely related to loading-bedding angle β. The general rule is that AE monotonously decrease as angle β increases. The slippage along the bedding at low angle β induces much more micro-cracks and damage compared to high angle β, which generates more AE counts at low angle β.



(a) β=0° (b) β=30°



(e) β=60° (f) β=90°

Figure 4. Variation in AE counts, accumulated AE counts and loading force of different β.

4 CONCLUSIONS

This study investigates the anisotropic Brazilian tensile strength (BTS) and failure behaviour of deep Longmaxi shale under Brazilian tests. The disk-shaped samples were cored parallel to (Group-P) and normal to (Group-V) the bedding planes. Seven loading direction-bedding angles β=0°, 15°, 30°, 45°, 60°, 75°, and 90° are considered. The main findings are summarized as follows: (1) It is observed that the BTS of deep Longmaxi shale has obvious anisotropy, which shows an ascend-slightly decline-ascend trend with angle β. (2) Comparison of predicted and experimental BTS, the reliability orders of five failure criteria are as follows: N-Z criterion > H-B criterion > L-P criterion > SPW criterion > MSPW criterion. The goodness-of-fit of N-Z criterion is more suitable for layered deep Longmaxi shale. (3) Observing from the failure of shale, there are four typical fracture patterns: central straight line fracture at β=0° and 90°, bedding activation shear failure fracture as β=15°, non-central arc fracture at β=30° and 45°, mixed mode fracture as β=60° and 75°. In particular, there is an inverse relationship between BTS and bedding activation fracture, that is, the bedding activation fracture decreases but the BTS increases gradually. (4) The cumulative AE counts-time curve exhibits a stepped increasing mode. And the AE counts are closely related to angle β, showing a monotonic decreasing trend with increasing of angle β.

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