Experimental Study on the Failure Mechanisms in Brittle Shales
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ABSTRACT: The brittle failure of Chengkou shale occurs throughout the exploration and development processes of hydrocarbons. To investigate the failure mechanisms of Chengkou shale and analyze the associated mechanical behavior such as crack initiation, propagation, and coalescence at different stress levels, a series of laboratory experiments were conducted on servo-controlled triaxial cells equipped with ultrasound monitoring. The experimental results show that key mechanical parameters such as peak stress $\sigma_{pp}$, stress onset of dilation $\sigma_d$, and strain at peak stress $\epsilon_p$ exhibit nearly linear relationships at various confining pressures. In rock bodies, the wave velocity evolution at different stress levels very consistently reproduces the shape of stress–strain curves, while shear wave velocity $v_s$ is more sensitive to crack damage than compressional wave velocity $v_p$. Furthermore, the Hoek–Brown failure criterion has an advantage over the Mohr–Coulomb fracture criterion due to the former’s higher correlation coefficient $R^2$. The wing crack damage models with sandwiched multilayers help explain the mixed tensile and shear failure mechanisms of Chengkou shale. The experimental results provide significant guidance for optimizing the design of drilling and well completion jobs, especially hydraulic fracturing operations, both in Chengkou shale and in other brittle shales around the world.

1. INTRODUCTION
Shale gas has become an increasingly important source of unconventional petroleum resources in China over the past decades. Shale gas is mainly stored in the pores of organic-rich matter.\textsuperscript{1,2} Compared with the conventional natural gas, shale gas development offers the advantages of a long recovery life and a long production cycle.\textsuperscript{3,4} Most shale gas plays are characterized by wide distribution, large thickness, and gas-bearing universality, which enable natural gas to be produced at an economical rate; thanks to advanced technologies such as horizontal well drilling and multistage hydraulic fracturing.\textsuperscript{5,6} China is thought to have the world’s largest reservoirs of unconventional gas, with an estimated 36 trillion cubic meters. This has significant potential and broad resource prospects for exploration and development in the future. Because organic-rich shale often abounds with quartz and clay minerals with some degree of natural fractures, rock failure is a very common occurrence throughout the process of petroleum exploitation and development. This process includes drilling and well completion operations and hydraulic fracturing treatments.\textsuperscript{7,8}

The deformation and damage failure of rock samples has been represented by stress–strain curves. The advantage of this method is its ability to directly reflect various deformation characteristics, including purely brittle, ductile, and cohesive fractures, under uniaxial force. In rock mechanics, the loaded mode can be classified into uniaxial and triaxial tests. The stress–strain curves of rock are typically divided into the following four stages: the microcrack closure stage, linear elastic stage, stable crack growth stage, and unstable crack growth stage.\textsuperscript{9–11} Brittle failure in a rock specimen refers to the rapid reduction of stress as the rock deformation increases. When the static Young’s modulus is generally in excess of 3.5 \times 10^6 \text{ psi} (about 24.1 \text{ GPa}), shale tends to be brittle, and the brittleness is associated with the shale’s complete lack of clay mineral content.\textsuperscript{12} However, brittleness cannot be estimated from the fraction of individual clay contents; rather, it depends on the proportion of each of the mineral components of the shale.\textsuperscript{4,13,14} When confining pressure increases, rock failure types gradually change from brittle to ductile. In the meantime, the brittle–ductile transition zone appears. Researchers\textsuperscript{3–15} have found that at ambient and elevated pressures and temperatures, shale samples show a transition from brittle to the semibrittle deformation behavior. Mechanical parameters such as rock strength and elastic moduli also increase with increasing confining pressure; hence, the failure mode shifts from axial splitting fracture to shear fracture.\textsuperscript{16} The constitutive behavior of cohesive fractures can be represented by a traction-
separation law that can approximate the nonlinear fracture process. The cohesive traction-separation law includes non-potential-based models (heuristic models) and potential-based models. Taleghani et al. proposed a triaxiality effect-based cohesive zone model that can capture the nonlinear behavior of shales. This model considers the total organic carbon and mechanical properties of cemented natural fractures in shales.

Fluid effects play an important role in both the compressive strength and tensile strength of the Woodford shale, whose clay content is mainly composed of illite and chlorite. Therefore, the failure mechanisms of brittle shales are very complex because it depends on many factors such as confining pressure, mechanical parameters, mineral composition, temperature, and fluid effects. An effective model to numerically simulate the failure mechanisms of brittle shales does not currently exist.

The change in ultrasonic acoustic wave velocities at different stress levels is another indicator of rock failure under compressive loads. In one study, the static (Young's modulus) and dynamic elastic parameters (P- and S-wave velocities) of shales generally decreased monotonically with the clay and kerogen contents; however, the viscoplastic creep strain was approximately linear with the applied deviatoric stress. Moreover, there was more viscoplastic creep behavior perpendicular to the bedding planes than parallel to the bedding planes, which correlated well with the static Young's modulus. For fine-grained granite samples, when the mean effective stress was lower than the initial stress point of dilation on stress–strain curves, the wave velocity increased with an increase in the deviator stress (referred to as \( \sigma_d - \sigma_i \)) because of microcracks closure in the early loading stage. When the deviator stress was beyond the abovementioned stress point, the wave velocity decreased with an increase in the deviatoric stress due to the microcracks initiation, propagation, and coalescence in the rock samples. The wave velocity of a crystalline rock decreased exponentially with the increasing number of fractures in the rock. Other parameters such as fracture characteristics, rock type, and scale effect may also contribute to velocity decay.

Typically, the P-wave velocity (referred to as \( v_p \)) decreases within the damage zone and increases in most regions outside the damage zone. In uniaxial stress cycling tests of Euville oolitic limestone, evolutions of the wave velocities reproduced very remarkably the shape of the stress–strain curves.

The failure behavior of different types of rocks can be described by fracture criteria such as the Mohr–Coulomb (MC) criterion, Griffith criterion, and Hoek–Brown (HB) criterion. Based on rock mechanics laboratory experiments, a comprehensive Griffith/MC fracture criterion was established, which is suitable for low-permeability sandstone reservoirs. When the value of minimum principal stress \( \sigma_2 \) is negative, the Griffith criterion is used for tensile fracture; when the value of minimum principal stress \( \sigma_4 \) is positive, the MC criterion is used for shear fracture. For brittle shales, however, the failure criterion is more complex because the mechanical and elastic parameters are related to the bedding planes and the clay and kerogen contents. Thus, shale samples cannot satisfy the aforementioned criterion of sandstone rock.

The brittle behavior of Opalinus clay shale was studied by Amann et al. using a triaxial compression test. The results showed that neither the MC nor the HB criterion was unable to satisfy all the experimental data under confining pressure. A bi- (or tri-)linear and S-shaped failure envelope was better able to describe the changes in the fracture process zone; however, the loading condition was under rapid compression at the rate of 0.10–0.15 mm/min. Combining nonlinear fracture mechanics and the discrete element method, Lisjak et al. studied the failure and damage behavior of Opalinus clay shale, taking into account the strength anisotropy of the shale. The numerical simulation results were generally consistent with the experimental observation results. However, the clay content of the Opalinus shale is more than 50%, making its failure mechanism different from that of the Chengkou shale (clay content 15%) investigated in this paper.

Chengkou shale has organic-rich content, well-developed micro-fractures, and bedding planes. These characteristics make it likely that Chengkou shale’s underlying failure mechanisms are different from those of other sedimentary rocks, such as tight sandstone, carbonate, and coal rocks. Although some scholars have investigated the failure mechanisms of the Opalinus shale, this type of shale is a clay shale rather than a brittle shale; moreover, their results are based on a rapid loading stress condition. The related failure mechanisms of the brittle shale remain underexplored. Knowledge about these mechanisms is critical for improving the level of risk management and reducing failure probabilities.

The goal of the present experimental study is to analyze the brittle failure behavior of the Chengkou shale by means of a combined laboratory triaxial compression test and ultrasonic acoustic velocity measurement. The related failure mechanism under different confining pressures is analyzed and discussed in detail. The experimental results provide significant guidance for the drilling engineering, well completion, and hydraulic fracturing operations of shale gas plays in Chongqing, a city in southwestern China.

The remainder of this paper is structured as follows. Section 2 presents the experimental results for uniaxial and triaxial conditions, including the elastic wave properties and anisotropy parameters of P/S-wave velocities, the rock deformation characteristics from the stress–strain curves, the characteristics of wave velocity variation with deviatoric stresses during incremental loading, and the corresponding fracture morphologies. In addition, we also discuss different criteria for the better prediction of the failure envelope in Chengkou shale. Section 3 summarizes the main conclusions of this paper. Section 4 presents the experimental setup and procedure, where the geological and physical characteristics of Chengkou shale is also included.

2. RESULTS AND DISCUSSIONS

2.1. Elastic Wave Velocity Properties of Shale Samples. As shown in Figure 1, the elastic wave velocities for each of the 52 shale samples are measured at normal temperature and atmospheric pressure. The figure illustrates that the P-wave and S-wave velocities of the rock samples along the longitudinal direction (referred to as \( v_p(L) \) and \( v_s(L) \), respectively) are in the range of 4.43–5.11 and 2.85–3.28 km/s, respectively; the P-wave and S-wave velocities along the radial direction (referred to as \( v_p(D) \) and \( v_s(D) \), respectively) are in the range of 4.3–5.17 and 2.76–3.43 km/s, respectively. This shows that there is a wide range of variation in \( v_p \) and \( v_s \), which indicates that Chengkou shale has a certain microscopic heterogeneity.

The brittleness index (BI) of each of these shale samples is calculated according to Rickman’s definition of brittleness, as shown in Figure 2. It is observed that the value of BI ranges...
from 40 to 80. The anisotropy parameters of the P/S-wave velocities (referred to as \( \varepsilon \) and \( \gamma \), respectively) are obtained according to eqs 11 and 12 in Section 4.4. In the figure, the wave velocity anisotropy is in the range of 0–18%, which suggests weak anisotropy; the anisotropy parameters for some samples are greater than 10%, which indicates some strong anisotropy among these samples.

The 52 shale samples can be divided into two groups: the first group of samples is drilled along the direction of the bedding planes, while the second group of samples is drilled normal to the bedding planes. The P/S-wave velocities for the two groups are compared in Figure 3. In the first group (Figure 3a), it is observed that the P/S-wave velocities along the radial direction of samples [referred to as \( v_p(D) \) and \( v_s(D) \), respectively] are greater than those in the longitudinal direction [referred to as \( v_p(L) \) and \( v_s(L) \), respectively] because the bedding orientation is approximately horizontal. However, in the second group, the wave velocities are found to be contrary to those of the first group (Figure 3b) because the bedding direction is approximately vertical. This indicates that the P/S-wave velocity variation strongly depends on the orientation of the bedding planes in rock samples.\(^{11,20}\)

2.2. Experimental Results under Uniaxial Stress. 2.2.1. Stress–Strain Relationship. The stress–strain curves of the shale samples under uniaxial stress are shown in Figure 4. The shale sample curves are compared with those of cement sample sn-1-1. The cement sample is man-made, which is a mixture of cement and ceramic as 2:1 volume ratio. For the shale samples, the microcrack closure stage occurs during early loading, and afterward, the rock samples enter the linear elastic deformation stage until rupture occurs (Figure 4a,b). In the postpeak stage, there are several stress–strain fluctuations (Figure 4a,b), which are characteristic of macroscopic fracture networks after peak stress \( \sigma_p \). In contrast to the shale samples, after the microcrack closure and linear elasticity stages, the cement sample shows the ideal elastoplastic characteristic from the stress–strain curve (Figure 4c) until macrofailure occurs.

2.2.2. Stress–Velocity Relationship. As stated above, in order to accurately identify the arrival time, cross-correlation waveform technology is adopted to determine the value of \( v_p \) at each stress level. Then, the stress–velocity curves of two shale samples (referred to as cls-1-11 and cls-1-12) are obtained, as shown in Figure 5. These curves reveal that the sample velocity changes with axial stress \( \sigma \) have the same variation trend. When axial stress \( \sigma \) reaches a critical stress value, the P-wave velocity \( v_p \) reaches its peak value. When the axial stress is lower than this value, the P-wave velocity \( v_p \) increases with an increase in \( \sigma \), which just corresponds to the microcrack closure stage during early loading; when \( \sigma \) is higher than this value, the
shale sample starts to experience the dilation stage from the stress–strain responses, and afterward crack propagation and coalescence occur in the sample. Beyond this dilation point, the wave velocity decreases with increasing axial stress $\sigma_1$ and ultimately macrofracture failure occurs in the rock sample. Therefore, the shape of the stress–velocity curve has good agreement with the stress–strain curves.

2.2.3. Fracture Morphology. The fracture morphology of these shale samples under uniaxial stress loading is shown in Figure 6. For shale samples, the main failure surface is a splitting crack along the axial direction of maximum principal stress $\sigma_1$. The fracture shapes are characterized by fracture networks, accompanied by some fragments. However, there is only one axial crack in the middle of the cement sample sn-1-1, and there are no fragments. The failure surface of cls-2-1 is very consistent with the orientation of the bedding planes, which helps explain the lower failure strength on the stress–strain curves.

2.3. Experimental Results under Triaxial Stress. 2.3.1. Stress–Strain Relationship. The stress–strain curves of the shale samples under triaxial stress conditions, which are very similar to those under uniaxial loading, are shown in Figure 7. The figure indicates that the stress–strain curves are mainly characterized by linear elastic deformation until macrofracture occurs. However, under different confining pressures, the number of stress–strain fluctuations in the
2.3.2. Stress–Velocity Relationship. Similar to the aforementioned approach of identifying the onset time, the relationship curve between wave velocity and axial stress $\sigma_1$ is shown in Figure 8. It is observed that the wave velocities ($v_p$ and $v_s$) have the same variation tendency as they do under uniaxial stress. However, S-wave velocity $v_s$ is more sensitive to artificial fractures than P-wave velocity $v_p$, as seen in the obvious velocity drop of $v_s$ in Figure 8b. This is because the value of shear wave velocity $v_s$ is lower than that of compressional wave velocity $v_p$. In fact, shear-wave splitting has received significant attention primarily because of its connection with vertically aligned fractures within reservoirs.

2.3.3. Fracture Morphology. The fracture morphology of the shale samples under triaxial stress is shown in Figure 9. For shale sample cls-1-4, it is observed that the angle between the main failure surface and maximum principal stress $\sigma_1$ is about $30^\circ$, indicating that the failure behavior of cls-1-4 is dominated by the shear-failure mode. The corresponding fracture geometry is characterized by fracture networks with some caving fragments when confining pressure $\sigma_3$ is equal to 5 MPa, which is consistent with the fracture morphology under uniaxial stress. For shale samples cls-1-5 ($\sigma_3 = 10$ MPa) and cls-1-15 ($\sigma_3 = 15$ MPa), the main failure plane becomes an

Figure 6. Fracture morphology of samples under uniaxial stress: (a) sample cls-1-2; (b) sample cls-2-1; and (c) sample sn-1-1.

Figure 7. Stress–strain curves under different confining pressures.

Figure 8. Stress-velocity curves of the sample cls-1-4 with confining pressure $\sigma_3 = 5$ MPa: (a) P-wave velocity $v_p$, and (b) S-wave velocity $v_s$. 

postpeak stage obviously decreases compared with that under uniaxial loading. This indicates that high confinement changes the failure processes.
inclined plane, indicating that the failure mode of these samples is also the shear-dominated type. The fracture pattern of the two samples is not as complex as that of sample cls-1-4, however, because of the higher confinement, which matches well with the identified stress–strain responses.

2.4. Discussions. 2.4.1. Stress–Strain Response. According to the stress–strain data in Figures 4 and 7, uniaxial and triaxial stress yield some key mechanical parameters, such as peak stress $\sigma_p$, elastic modulus $E$, and Poisson’s ratio $\nu$, as shown in Table 1, where $\epsilon_p$ is the strain at peak stress $\sigma_p$.

| core number | $\sigma_p$ (MPa) | $\sigma_1$ (MPa) | Young’s modulus (GPa) | Poisson’s ratio | $\epsilon_p$ (%) | $\sigma_3$ (MPa) |
|-------------|-----------------|-----------------|-----------------------|----------------|----------------|----------------|
| cls-1-2     | 110             | 0               | 21.7                  | 0.13           | 0.57           | 60             |
| cls-2-1     | 28              | 0               | 8.2                   | 0.13           | 0.33           | 17.6           |
| sn-1-1      | 49.4            | 0               | 11.4                  | 0.26           | 0.56           | 26.9           |
| cls-1-4     | 163             | 5               | 31.6                  | 0.21           | 0.65           | 87.9           |
| cls-1-5     | 127             | 10              | 33.3                  | 0.16           | 0.45           | 70.4           |
| cls-1-15    | 199             | 15              | 27.9                  | 0.34           | 0.72           | 116.5          |

Under uniaxial stress, the values of $\sigma_p$ and $\sigma_3$ for sample cls-1-2 (drilled normal to the orientation of the bedding planes) are about four times those of the sample cls-2-1 (drilled parallel to the orientation of the bedding planes). The reason is that the orientation of the bedding planes for sample cls-1-2 is normal to the direction of axial stress $\sigma_1$, while the orientation of the bedding planes for sample cls-2-1 is parallel to the direction of $\sigma_1$. In addition, for sample cls-1-2, crack closure occurs during the early loading stage, and the stress–strain response is strongly concave upward. The orientation of the bedding planes thus has an obvious influence on static parameters in rock mechanics. Hu et al. pointed out that the mechanical properties of interbedded sandstones are significantly influenced by stress levels and structural anisotropy. In fact, the anisotropic behavior of rock samples can be attributed to the interaction between the matrix and the bedding plane deformation, which depends on the loading orientation.

As shown in Figure 10, under triaxial stress, the mechanical parameters show a linear growth trend with increasing confining pressure $\sigma_\text{c}$. This indicates that the failure process satisfies the MC criterion, which is the most widely used failure criterion in rock mechanics and rock engineering. It also reveals that the failure strength of the Chengkou shale is a linear function of confining pressure. However, sample cls-1-5 is an exception because of its mechanical heterogeneity. Thus, the information of cls-1-5 ($\sigma_3 = 10 \text{ MPa}$) is not considered in Sections 2.4.2 and 2.4.3. As confinement is applied to shale samples, the orientation and magnitude of the stress on the given plane increases, leading to frictional resistance and an associated rock strength increase. For the same argillaceous limestone specimen, the residual strength has a good linear relationship with the confining pressure, which is consistent with the results in this study.

The relationship curve between volumetric strain $\epsilon_v$ and axial stress $\sigma_1$ at different levels of confining pressure in the prerupture phase is shown in Figure 11. The results show that the volumetric behavior is purely contractive when confining pressure $\sigma_3$ is greater than or equal to 15 MPa. When the value of $\sigma_3$ is less than that, the volumetric strain is dilatant. Volumetric strain $\epsilon_v$ is defined as the summation of the axial strain $\epsilon_\text{a}$ and twice the radial strain $\epsilon_\text{r}$, that is, $\epsilon_v = 2\epsilon_\text{r} + \epsilon_\text{a}$. Therefore, volumetric strain remains contractive only if $\epsilon_\text{a}$ is greater than $2\epsilon_\text{r}$. We deduce that volumetric contraction is due to accelerating axial compaction accompanied by steady or even decelerating circumferential expansion. Under the relatively high confinement of 15 MPa, the rate of circumferential expansion slows down. Figure 9c shows that local failure occurs on the slope, accelerating axial compaction. Therefore, volumetric contraction is related to strain localization and the shear-enhanced compaction band in rock samples.
2.4.2. Stress—Velocity Response. As Toksöz et al.\textsuperscript{42} pointed out, variation in ultrasonic velocity may reflect the degree of damage in a rock well. The damage index is defined as:\textsuperscript{43}

\begin{equation}
D = 1 - \frac{E}{\bar{E}}
\end{equation}

where $E$ and $\bar{E}$ are Young’s modulus values of the intact and damaged rock, respectively, and $D$ is the damage factor.

In addition, compressional wave velocity $v_p$ can be calculated using rock mechanics parameters. The corresponding expression can be written as:\textsuperscript{9}

\begin{equation}
v_p = \sqrt{\frac{E(1-\nu)}{\rho(1+\nu)(1-2\nu)}}
\end{equation}

where $\rho$ is rock density, and $\nu$ is Poisson’s ratio.

Substituting eq 2 into eq 1, the damage factor may be associated with the wave velocity as follows:\textsuperscript{44}

\begin{equation}
D \approx 1 - \left(\frac{v_s}{v_p}\right)^2
\end{equation}

where $v_s$ denotes the P-wave velocity of the intact rock at room temperature and atmospheric pressure.\textsuperscript{44}

Based on the ultrasonic velocity data for sample cls-1-4 (confining pressure $\sigma_3 = 5$ MPa), Figure 12 shows the change in the damage factor $D$ with different levels of axial stress $\sigma_1$, which satisfies a good fitted quadratic polynomial relationship.

On the other hand, the crack density is an important dimensionless parameter that may reflect the degree of damage when loading. According to noninteractive effective medium theory, the crack density can be calculated using ultrasonic velocities $v_p$ and $v_s$:\textsuperscript{45,46}

\begin{equation}
\rho_c = \left(\frac{\rho_0}{\rho} - 1\right)\left(1 + \nu_0\right)\frac{1}{h\left(1 - \frac{\nu_0}{5}\right)}
\end{equation}
This relationship between shear stress and normal stress on the slope is expressed as
\[ \tau = \sigma_n \tan(\phi) + c \]  
(8)
where \( \tau \) denotes the shear stress along the slope, \( \sigma_n \) denotes the normal stress on the slope, \( \phi \) denotes the internal friction angle, and \( c \) denotes the cohesive strength of the rock mass.

The HB criterion is derived from the results of research on the brittle failure of intact rock by Hoek and the model studies of the jointed rock mass behavior by Brown.\textsuperscript{36,47} It is defined by the following equation
\[\sigma_i = \sigma_3 + \text{UCS} \left( m_b \frac{\sigma_3}{\text{UCS}} + s \right)^{1} \]  
(9)
where UCS denotes uniaxial compressive strength; \( m_b \) is the value of the HB constant for the rock mass; and \( s \) and \( a \) are constants which depend on the characteristics of the rock mass (\( s = 1 \) for intact rock). The equivalent MC criteria can also be obtained according to Hoek and Brown’s research.\textsuperscript{28}

Based on the data in Table 1, the coefficient of correlation \((r^2)\) and constitutive properties for the MC and the HB failure criteria are listed in Table 2. The failure envelopes are plotted in Figure 14. The HB criterion has an advantage over the MC criterion for the Chengkou shale because of its higher correlation coefficient. This advantage is due to some natural fractures and the bedding planes involved in the failure process.

| \( r^2 \) | UCS (MPa) | \( \Phi \) (deg) | \( c \) (MPa) | \( M \) (-) | \( s \) (-) |
|---|---|---|---|---|---|
| MC | 0.91 | 110 | 44.2 | 25.4 |
| HB | 0.99 | 110 | 45.8 | 20.9 | 13.1 | 1 |

2.4.4. Other Discussions. Brittle failure can be modeled using sliding wing crack damage models.\textsuperscript{48} Based on the results from Ashby and Sammis,\textsuperscript{49} wing cracks are expected to start to initiate from pre-existing flaws when axial stress \( \sigma_i \) is equal to

Figure 12. Damage factor versus axial stress relationships for sample cls-1-4 (\( \sigma_3 = 5 \) MPa).

Figure 13. Crack density versus axial stress relationships for sample cls-1-4 (\( \sigma_3 = 5 \) MPa).

Figure 14. Fracture criterion for Chengkou samples.
\[
\sigma_1 = \frac{\sqrt{1 + \mu^2 + \mu}}{\sqrt{1 + \mu^2 - \mu}} \sigma_3 + \frac{\sqrt{3}}{\sqrt{1 + \mu^2 - \mu}} K_{IC}
\]

where \( K_{IC} \) denotes fracture toughness; \( \mu \) denotes the friction coefficient of pre-existing flaws; and \( a_i \) denotes the length of pre-existing flaws, which is usually in the range of 100–300 \( \mu \)m.

Based on the parameters in Tables 1 and 2, the fracture toughness of the Chengkou shale \( K_{IC} \) is estimated to be in the range of 0.52–0.90 \( \text{MPa-m}^{1/2} \), which is consistent with the experimental results of previous researchers. This indicates that wing crack models are well-suited for representing the damage evolution of the Chengkou shale. Meanwhile, wing crack models are a possible interpretation of the linear variation of mechanical parameters with confinement in Section 2.4.1.

Because of the bedding planes that are normal to the direction of axial stress \( \sigma_1 \), the shale samples can be seen as layered rock consisting of both quartz and clay. Most studies have used the sandwiched three-layer model to explain the failure mechanisms in brittle rocks, as shown in Figure 15. In this model, the elastic modulus \( E_2 \) is less than that of the rock matrix \( E_1 \), and thus, the bedding planes are considered the soft layer, and the rock matrix is seen as the stiff layer. Bourne presented an exact analytic solution of multilayered media composed of \( N \) coupled, fully elastic horizontal layers under the action of uniform remote stress; this model was fully coupled with elastic horizontal layers in three dimensions. The solution showed that a tensile stress is formed in a layer under a remote compressive stress if that layer was associated with another sufficiently softer and thicker layer. The local slip could occur at the interface of bedding planes (Figure 15b). The wing cracks could then be generated in the soft layer because of the interaction of the axial cracks in the stiff layer. Finally, fracture coalescence and the macrofracture failure could occur in the rock mass. Therefore, the mixed tensile and shear failure could occur simultaneously in the loading process. This is a better explanation for the failure mechanisms of the brittle Chengkou shale than only tensile or shear failure is.

3. CONCLUSIONS

This paper investigated the failure mechanisms of the brittle Chengkou shale by means of a series of triaxial rock mechanics experiments with acoustic wave velocity monitoring. The following conclusions can be drawn from this study:

1. The experimental results related to elastic wave velocity at room temperature and atmospheric pressure show that there is a certain microscopic heterogeneity in Chengkou shale samples. The overall performance is weak anisotropy, but the anisotropy of some rock samples is very strong. This indicates that the orientation of the bedding planes and natural fractures have a great impact on the wave velocity and anisotropy parameters.

2. The wave velocity experiments under uniaxial and triaxial stress show that before the onset of dilation on stress–strain curves, the wave velocity of the shale samples increases with the increase in axial/deviator stress. This increase is caused by the microcrack closure. Beyond the dilation point, the wave velocity decreases gradually due to crack initiation, propagation, and coalescence at an elevated load.

3. Under uniaxial stress conditions, the stress–strain curve of shale samples is quite different from that of the cement sample. Before a shale sample fails, it can be mainly characterized by linear elastic deformation. In the postpeak stage, the stress–strain curve fluctuates repeatedly and corresponds to the observed characteristics of fracture networks. The cement sample has obvious plastic deformation characteristics in the prerupture phase, and the stress–strain curve quickly falls off beyond the peak stress. This shows that the Chengkou shale has good fracability with a strong brittleness index.

4. When the confining pressure is lower than 15 MPa, the Chengkou shale sample meets the MC failure criterion. With an increase in confining pressure \( \sigma_3 \), failure strength \( \sigma_p \), strain at peak stress \( \epsilon_p \) and stress onset of dilation \( \epsilon_{ci} \) increase linearly. When the confining pressure is lower than the critical value, the sample forms splitting cracks, and the failure patterns gradually change from the tensile-dominated mode to the shear-dominated mode.

5. The wave velocity evolution at different stress levels reproduces very consistently the shape of stress–strain curves. However, in rock bodies, shear wave velocity \( v_s \) is more sensitive to crack damage than compressional wave velocity \( v_p \). Furthermore, the HB failure criterion has an...
advantage over the MC fracture criterion due to the former’s higher correlation coefficient $r^2$.

(6) The wing crack damage models with sandwiched multilayers are a good explanation of the mixed tensile and shear failure mechanisms of the brittle Chengkou shale. It is necessary to carry out more experimental research on these failure mechanisms in order to establish a foundation for the ground stress, wellbore stability, and the volume fracturing mechanism of the gas shale in China.

4. EXPERIMENTAL SETUP AND PROCEDURE

4.1. Description of the Chengkou Shale. The Chengkou shale is deposited in the Lower Cambrian Lujiaping formation in the northeast part of the upper Yangtze area, Chongqing, China. Two lithofacies, that is, the carbonaceous shale and carbonaceous silty shale, have been identified in Lujiaping formation. Both of these shales have a high gas content and large layer thickness, with a maximum layer thickness of 800 m. The carbonaceous shale is mainly buried in the lower part of Lujiaping formation, with a thickness of 100–300 m. The organic carbon content is in the range of 1.79–10.40%, with an average value of 5.60%, which indicates that it is a high-quality source rock.

X-ray diffraction indicates that the mass fractions of the predominant mineralogical components of the Chengkou shale are quartz (57.2%), calcite (17.1%), clay (15.1%), albite (4.9%), dolomite (3.8%), and pyrite (1.9%). Among the clay minerals, illite (75%) is the most abundant.

The porosity of the Chengkou shale is in the range of 4.00–6.00%, and the average porosity of the shale samples is 4.37%; the permeability of the Chengkou shale varies between $10^{-6.00}$, and the average porosity of the shale samples is 4.37%; the permeability of the samples is $10^{-4}$–$10^{-3}$ mD, and the average permeability of the samples is $5.6 \times 10^{-4}$ mD. Mercury porosimetry data suggest that 46.8% of the pores are macropores (equivalent radius >1000 nm), 21.3% are mesopores (equivalent radius 100–1000 nm), 25.5% are transition pores (equivalent radius 10–100 nm), and 6.4% are micropores (equivalent radius <10 nm). These observations show that a large portion (72.3%) of the pores is composed of macropores and transition pores. A scanning electron microscope (SEM) shows that the degree of the overall pore development of shale samples is not abundant with the irregular pore morphology, as shown in Figure 16. The organic matter is relatively undeveloped, and there are only a few organic nanopores among the inorganic mineral particles, where the organic matter is often associated with raspberry-like pyrite. The mineral pores mainly include intergranular pores and dissolution pores, with intergranular pores being dominant. There are a large number of tiny holes and cracks in the shale samples; these holes and cracks are mostly structural joints and intergranular pores. Microcracks are mostly present in the interior of the particles and on the edges of the crumb particles, with fracture lengths of several micrometers.

4.2. Sample Preparation. The outcrop shale samples are cored from Lujiaping formation, which is located in Chongqing County, in the city of Chongqing, in southwest China. These samples are drilled to the International Society for Rock Mechanics (ISRM)-suggested cylindrical shapes with a 25 mm diameter and 50 mm height. The sample ends are polished to ensure minimum friction with the platens during loading.

4.3. Experimental Setup. The ultrasonic wave velocity measurement system is composed of an Olympus 5077PR electric pulse generator/receiver and an oscilloscope. To test the wave velocities of the rock samples at normal temperature and atmospheric pressure, a pair of V157 shear wave transducers with a 3 mm diameter are used. To improve the contact area between sample ends and transducers, a special U-shaped tool and coupling agent are adopted in this experiment.

The triaxial testing machine with high temperature and high pressure is used to conduct the experiments. The maximum capacity value of the axial load is 1000 kN, and both the maximum confining pressure and maximum pore pressure are equal to 140 MPa. There is a pair of ultrasonic (1 MHz) P/S-wave transducers embedded in the loading platens, which are able to monitor changes in ultrasonic wave velocities with deviatoric stress (referred to as $\sigma_{1}-\sigma_{3}$) under triaxial loading conditions. The linear variable differential transformer technique is adopted to accurately measure the axial and circumferential strains under load. The rock samples are wrapped with a polyethylene heat-shrink tube to protect the samples from silicone oil.

4.4. Experimental Procedure. First, we use the ultrasonic wave velocity system to test the elastic properties of shale samples, that is, P/S-wave velocity and its anisotropy at room temperature and atmospheric pressure. Then, we calculate the wave anisotropy parameters $\varepsilon$ and $\gamma$ using Thomsen’s equations, which are expressed as

$$
\varepsilon = \frac{\ln(v_L) - \ln(v_S)}{\ln(v_L) - \ln(v_P)} \times 100
$$

(11)

$$
\gamma = \frac{\ln(v_L) - \ln(v_D)}{\ln(v_L) - \ln(v_P)} \times 100
$$

(12)

Second, the shale samples are compressed by applying axial stress (referred to as $\sigma_1$) from the Geotechnical and Consulting Testing Systems (GCTS) machine with a constant strain rate 2

Figure 16. SEM results of the Chengkou shale: (a) microcracks, (b) raspberry-like pyrite, (c) intergranular pores, and (d) organic matter.
\( \times 10^{-6} \text{ s}^{-1} \) under uniaxial and triaxial stress conditions, respectively. For each sample, the confining pressure (referred to as \( \sigma_1 \)) is assigned as either 0, 5, 10, or 15 MPa in order to obtain the failure envelope. Meanwhile, the elastic P-wave velocity along the axial direction of the samples [referred to as \( v_t(L) \)] is measured when loading. In order to ensure the measuring accuracy of wave velocity, the waveform cross-correlation method is utilized to determine the arrival time at each stress level.\(^{21,25}\) To select the velocity’s arrival time at each stress level, a total of 100 waveforms are stacked to improve the signal-to-noise ratio.\(^{8,25,34}\) This cross-correlation technique helps to determine the time arrival of the P/S-wave through waveform relative locations,\(^{21}\) which can be expressed as

\[
\frac{\delta v}{v} = -\frac{\delta t}{t} \tag{13}
\]

where \( \delta v \) is the velocity change between adjacent waveforms; \( \delta t \) is the travel-time shift caused by \( \delta v \); and \( v \) is the wave velocity at the time \( t \).

4.5. Method of Determining the Damage Stress Threshold. There are two damage stress thresholds on the stress-strain curves, that is, the crack initiation and propagation thresholds (referred to as \( \sigma_{ci} \) and \( \sigma_{cd} \), respectively), as shown in Figure 17. These thresholds are two key components in the brittle-fracture process.\(^{5,6,35-60}\) Crack initiation stress threshold \( \sigma_{ci} \) refers to the point where the stress-volumetric strain curve departs from the linear trend, and crack propagation stress threshold \( \sigma_{cd} \) is defined as the reversal point of the stress-volumetric strain curve.\(^{31,49,56}\)

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**Notes**

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**NOMENCLATURE AND UNITS**

| Symbol | Description |
|--------|-------------|
| E      | Young’s modulus, GPa |
| G      | Poisson’s ratio, dimensionless |
| \( \nu \) | shear modulus, GPa |
| \( \tau \) | normal stress, MPa |
| \( \sigma_1 \) | shear stress, MPa |
| \( \phi \) | internal friction angle, deg |
| \( c \) | cohesive strength, MPa |
| \( a, s, m \) | material constants, dimensionless |
| \( \sigma_1 \) | maximum principle stress, MPa |
| \( \sigma_3 \) | minimum principle stress or confining pressure, MPa |
| \( \sigma_{ci} \) | crack initiation stress that is defined by the onset of dilation, MPa |
| \( \sigma_p \) | peak stress, MPa |
| \( \epsilon_p \) | strain at peak stress, MPa |
| \( \epsilon_x \) | axial strain, dimensionless |
| \( \epsilon_r \) | radial or circumferential strain, dimensionless |
| \( S_d \) | deviatoric stress, MPa |

\[ \sigma_1 - \sigma_3 \]
P-wave velocity, km/s

P-wave velocity along the axial and radial directions of samples, km/s

S-wave velocity, km/s

S-wave velocity along the axial and radial directions of samples, km/s

\( e, \gamma \) anisotropy parameter of \( v_p \) and \( v_s \), dimensionless

BI brittleness index, dimensionless

UCS uniaxial compressive strength, MPa

\( \rho \) rock density, g/cm³

\( \rho_c \) crack density, dimensionless

\( D \) damage factor, dimensionless

\( K_{IC} \) fracture toughness, MPa·m¹/²

\( a_i \) length of pre-existing flaws, µm

\( \mu \) friction coefficient of pre-existing flaws, dimensionless

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