Experimental Study on the Uniaxial Compression Failure and Ultrasonic Transmission of Brittle Shale Considering the Bedding Effect

JIE LIU, YONGLI ZHANG, XINLE YANG, AND CHANG SU

School of Mechanics and Engineering, Liaoning Technical University, Fuxin 123000, China

Corresponding author: Jie Liu (arwenliu@126.com)

This work was supported in part by the National Science and Technology Major Project under Grant 2017ZX05037-001; in part by the National Natural Science Foundation of China under Grant 51574138, Grant 51574136, and Grant 51604275; in part by the Liaoning Revitalization Talent Program under Grant XLYC1807150; and in part by the Natural Science Foundation of Liaoning under Grant 2019-d-0035.

ABSTRACT

The rock failure process, especially the crack propagation process in rock, can essentially reveal many mechanical problems in the rock. The bedding structure of shale is one of the main influencing factors of rock failure. This study performed an ultrasonic dynamic transmission test on Longmaxi Formation shale specimens with different bedding angles under uniaxial compression and comprehensively analyzed the mechanical and ultrasonic evolution characteristics. The deformation and failure of the shale samples indicated obvious brittle characteristics, and the final failure mode was dominated by shear cracks along the bedding planes and tensile-compressive cracks along the maximum principal stress direction. The difference index of the bedding calculated by the ultrasonic response speed showed that with increasing deformation and failure, the influence of the bedding structure on the failure decreased. In the process of uniaxial compression, the ultrasonic transmission velocity changed periodically. Relying on the obvious jumping points of the ultrasonic velocity curve, we could initially judge the possible key points of the changes in the pores and cracks during the rock failure process. A new method to calculate the rock brittleness index based on the characteristic response velocity of ultrasonic waves was proposed. Compared with the classical method, this method revealed a good applicability. This study can further clarify the relationship between the acoustic characteristics of ultrasonic transmission and rock deformation and failure, and can lay a certain theoretical foundation for the subsequent study of ultrasonic transmission and rock structure, along with its mechanical, physical and chemical properties.

INDEX TERMS

Bedding, failure evolution, ultrasonic wave velocity, brittleness.

I. INTRODUCTION

Cracking is the root cause of all geological behaviors. To clarify seismic damage, rock modification under pressure, and many other rock mechanics problems, the first step is to determine the rock failure processes, especially crack propagation. The bedding structure of shale is one of the main influencing factors of rock failure, and the deformation and failure differ significantly from those of dense rocks.

Accurately ascertaining and describing the details of the rock deformation and failure (crack propagation in rock) processes raises a complex problem. Currently, most studies still rely on experiments to solve this problem, such as acoustic emissions, CT scans, industrial MRI scans, and ultrasonic waves. Ultrasonic waves, as a type of ideal information carrier, can reflect the physical-mechanical indices and meso-structural characteristics of rocks through inversion based on changes in acoustic information, such as wave velocity and attenuation coefficient.

As early as the middle of last century, scientists had already noticed that the propagation characteristics of ultrasonic waves in rock could be used to analyze the physical-mechanical properties of rock [1], [12], [19]. They also explored the causes of anisotropy in ultrasonic wave velocity and attenuation [5], [6], [10]. Dewhurst et al. [6] and investigated how stresses on microstructures (including
granules, laminations, and microcracks) parallel to shales (marine shales in Norway) would affect the elastic wave velocity and elastic wave velocity anisotropy. Deng et al. [10] examined the variation rules of P-wave and S-wave velocities with pressure in mudstones and shales based on indoor tests and deduced that clay minerals and microfractures were the primary causes of anisotropy.

Some scholars have examined the effect of bedding structures and other natural defects of rocks on ultrasonic propagation. Vernik and Nur [13] found that black shales have a strong anisotropy, ultrasonic waves perpendicular to bedding planes have a low velocity, and cracks parallel to bedding planes can enhance anisotropy. Taking the Longmaxi Formation shales as the object of study, Xiong et al. [11] and Lu et al. [23] conducted an ultrasonic transmission test on shale cores with different bedding angles and determined that there is a positive linear relationship between the P-wave and S-wave velocities, where the P-wave and S-wave velocities and the attenuation coefficient decreased with an increasing bedding angle and that the P-wave and S-wave velocities in shales had significant linear positive correlations with both the core density and bedding density. Deng et al. [22] performed ultrasonic wave velocity tests on bedded shales under triaxial compression, identified relationships between the mechanical parameters (such as the elastic modulus and Poisson’s ratio) and bedding angle, and determined that the P-wave and S-wave velocities first increase and decrease afterwards with an increasing axial load. Xu et al. [7] effectively simulated ultrasonic transmission through bedded rocks using numerical simulations and claimed that the acoustic velocity was a conventional sensitive factor characterizing shale bedding structures, that the attenuation coefficient was sensitive to changes in the bedding thickness, and that the simulation results fit well with the test results.

The deformation and failure process of a rock can be seen as the process of initiation and propagation of internal cracks, which is closely related to rock macroplasticity and strength. A few scholars have linked ultrasonic propagation with rock deformation and failure, and have studied the deformation failure process of rocks based on the ultrasonic propagation of cracks [3], [14], [18], [21]. Sayers [3] constructed a directional distribution function for cracks in rocks using the ultrasonic wave velocity, which was used to predict the directional distribution probability of cracks. Wang et al. [21] simulated the hydraulic fracturing of shales using similar materials and acquired the overall crack width based on the ultrasonic pulse velocity (UPV), thus analyzing the evolution of crack networks and evaluating the effect of hydraulic fracturing.

Focusing on natural shale samples with beddings, this study placed specimens with different bedding angles (i.e., 0°, 30°, 60°, and 90°) under uniaxial compression, conducted an ultrasonic transmission test, and extracted the stress, strain, and acoustic velocity properties of specimens during deformation and failure to comprehensively analyze the deformation failure process of shales containing natural beddings. This study can further clarify the relationship between the acoustic characteristics of ultrasonic transmission and rock deformation and failure, and can lay a certain theoretical foundation for the subsequent study of ultrasonic transmission and rock structure, along with its mechanical, physical and chemical properties.

II. TEST OVERVIEW
A. SHALE SAMPLES AND SPECIMEN PREPARATION

The shale samples used in this test were collected from the shale outcrop of the Weiyuan National Shale Gas Demonstration Zone in Changning County, Yibin, Sichuan Province, China. The strata in Changning are characterized by a large thickness, a high organic content, fine petrophysical properties, stable regional distribution, and simple geological structures. The Longmaxi Formation in Changning is an extension of one of the earliest important shale gas fields discovered in China. The shale outcrops in the demonstration area were collected, and the weathered layer on the surface was stripped. Large shale raw stone with obvious sedimentary bedding was selected and processed into cubic specimens 400 mm×400 mm×400 mm in size (Fig. 1).

The structural characteristics of the pores in the shale samples were measured using a QUANTA 250 electron scanning microscope (×100-30,000). The shale samples contained many pore spaces and abundant pore types, including intergranular pores, interlayer pores, pores between mineral crystals, and significant microfractures (Fig. 2). The mineral compositions of the shale sample were analyzed using an X-ray diffractometer. The quartzite content was the highest (63.1%), followed by calcite (13.1%) and Muscovite (8.5%), a small amount of chalcopyrite (0.5%), kaolinite (0.6%) and dolomite (1.6%), and a small amount of clay (3.9%) (Fig. 3).

The pore space, mineral composition and symbolic appearance of the rock samples had typical characteristics of the Lower Silurian Longmaxi Formation shale, which could be judged as black silicon rich parallel laminated shale [2], [4]. The content of brittle minerals was very high, and it had...
FIGURE 2. Scanning images of pore structure of shale samples.

FIGURE 3. Relative mineral contents of shale samples from X-ray diffraction (XRD) analysis.

B. TEST APPARATUS AND METHOD

The test was conducted using a Geotechnical Consulting and Testing Systems (GCTS)–RTR-1000 rock testing system (Fig. 4). The system not only supports the triaxial loading test but also has ultrasonic emission and signal collection and processing functions. The GCTS apparatus can be pressure- or volume-controlled using a digital closed-loop servo, and adopts a double-piston pressurization system without low-frequency noise transmission. The GCTS measures strains using high precision axial and lateral strain gauges with a maximum axial load of 1,000 kN, a maximum confining pressure of 140 MPa, and a resolution of 0.01 MPa. The acoustic acquisition system was a ULT-100 ultrasonic controller, which has both automatic anti-aliasing filtering and can automatically switch between P-waves and S-waves. The ultrasonic wave sampling frequency is 20 MHz. The tester indenter used a bearing-type acoustic transducer with a P-wave and S-wave central exciting frequency of 1 MHz and a measurement precision of 0.1 µs. An oscilloscope was connected to a computer to automatically connect the acoustic information during loading. Uniaxial compression was employed for strain loading at a rate of 1.25 × 10⁻⁴ mm/s. P-waves and S-waves were transmitted through shale specimens with loading. The acquisition system was used to dynamically collect the stress and strain of the shale specimens, as well as the relevant acoustic information. The ultrasonic processing software Cats Ultrasonic was used to process the acoustic signals.

III. CHARACTERISTICS OF THE FAILURE EVOLUTION PROCESS

A. FAILURE CHARACTERISTICS

Due to differences in the bedding angle and natural crack distribution, the failure process and failure mode of the shale specimens vary significantly (Fig. 5).

(1) The specimen with a bedding angle of 0° (hereinafter referred to as “the 0° specimen”) showed multiple primary cracks along the maximum principal stress direction, which intersected with the horizontal bedding planes. Because of the weak cementation of the bedding planes, primary cracks propagated along the bedding planes and eventually formed larger splitting blocks. Under the external loads, these blocks could easily slide along the bedding planes, causing widespread damage composed of splitting and sliding along the bedding planes (Fig. 5 (a)).

(2) The failure mode of the 90° specimen was similar to that of the 0° specimen. That is, it also showed primary

TABLE 1. Natural parameters of shale specimens.

| Specimen label | Height/mm | Diameter/mm | Quality/g | Bedding angle/° |
|----------------|-----------|-------------|-----------|-----------------|
| 0-1            | 100.54    | 50.03       | 458.90    | 0               |
| 0-2            | 99.75     | 50.15       | 460.75    | 0               |
| 0-3            | 99.88     | 49.88       | 450.39    | 0               |
| 30-1           | 101.17    | 50.23       | 469.50    | 30              |
| 30-2           | 101.47    | 50.06       | 468.60    | 30              |
| 30-3           | 101.25    | 50.04       | 470.53    | 30              |
| 60-1           | 101.40    | 50.14       | 458.46    | 60              |
| 60-2           | 102.00    | 50.10       | 461.79    | 60              |
| 60-3           | 101.57    | 50.25       | 460.88    | 60              |
| 90-1           | 101.19    | 50.31       | 456.15    | 90              |
| 90-2           | 100.95    | 50.17       | 455.29    | 90              |
| 90-3           | 101.86    | 50.28       | 459.80    | 90              |

VOLUME 8, 2020

217885

J. Liu et al.: Experimental Study on the Uniaxial Compression Failure and Ultrasonic Transmission
cracks along the maximum principal stress direction, accompanied by the development of several transverse secondary cracks. The analysis revealed that these secondary cracks were shear failures produced by the bedding plane friction and axial stress as the specimen failed along bedding planes (Fig. 5 (d)). The difference between the 90° specimen and the 0° specimen lies in that, for the former, the maximum principal stress direction overlapped with the bedding direction, which made it easier for cracks to form along the maximum principal stress direction.

(3) The failure modes of the 30° specimen and the 60° specimen were quite similar. First, primary shear cracks formed along the weak bedding plane at one site or several sites in the shales, and these cracks gradually propagated, together with the emergence of multiple secondary compressive-shear cracks along the maximum principal stress direction. With the progressive interconnection of various primary and secondary cracks, the specimens ultimately failed. While the macroscopic primary cracks along the weak bedding plane constituted the main cause of the instability failure of the shale specimens, the secondary cracks along the maximum principal stress direction weakened the bedding plane friction to some extent (Fig. 5 (b) and (c)).

B. CHARACTERISTICS OF THE STRESS-STRAIN CURVE

Due to the presence of defects (such as joints, bedding, fractures, micropores, and microcracks) in shales, the failure of shales under external loads is essentially a process consisting of gradual growth and propagation of original cracks, continuous initiation of new cracks, and progressive interconnection and penetration of cracks in shales. The stress-strain curve can be used to analyze the macroscopic

FIGURE 5. Comparison of the sketches of cracks of the failed specimens: (a) Bedding angle is 0°; (b) Bedding angle is 30°; (c) Bedding angle is 60°; (d) Bedding angle is 90°.
mechanical properties manifested by shales with crack evolution during uniaxial loading.

Test data was used to draw the axial stress-axial strain, the circumferential strain, and the volume strain curves of various shale specimens, then the crack evolution stage was divided, and the characteristic points of the process were extracted (the method to determine the characteristic stress is referred to in Zhang et al. [15]; crack initiation stress is represented by \( \sigma_{ci} \), critical dilatancy stress is \( \sigma_{cd} \), and peak stress is \( \sigma_f \)). The Young’s modulus and Poisson’s ratio were calculated (Fig. 5, Fig. 6, Fig. 7, Fig. 8, Table 2). The volume strain can be calculated from (1).

\[
\varepsilon_v = -\varepsilon_1 + 2\varepsilon_2 \tag{1}
\]

where \( \varepsilon_v \) denotes the volume strain (volume compression is “-”, volume expansion is “+”); \( \varepsilon_1 \) denotes the axial strain (volume compression is “-”); and \( \varepsilon_2 \) denotes the circumferential strain (compression is “-”, expansion is “+”).

\[
\sigma_f = (\sigma_1)_{\text{max}} \tag{2}
\]

\[
YM = (\sigma_1)_{50}/(\varepsilon_1)_{50} \tag{3}
\]

\[
PR = \left| \varepsilon_d^s/\varepsilon_h^s \right| \tag{4}
\]

where \( YM \) is Young’s modulus, GPa; \( PR \) is Poisson’s ratio, %; \( (\sigma_1)_{50}, (\varepsilon_1)_{50} \) denotes the axial stress under a uniaxial compressive strength of 50%, MPa; \( (\varepsilon_1)_{50} \) denotes the axial strain corresponding to \( (\sigma_1)_{50} \), %; and \( \varepsilon_d^s, \varepsilon_h^s \) denote the mean axial strain and mean radial strain of the linear elasticity phase, respectively, %.

The failure process of the shale specimens under uniaxial compression conformed to the failure characteristics of typical brittle rocks. The crack closure stage of each specimen was not obvious (no crack closure stage was found in specimen 0-2), which indicated that the specimens were dense; however, both the linear elasticity phase and crack propagation phase could be clearly observed in all specimens (Fig. 6). Both 30° specimens showed a strong resistance to failure, with higher initiation points (\( \sigma_{ci} \)) and peak points (\( \sigma_f \)) (Fig. 7) and longer linear elastic stages (the 30-3 specimen had the longest linear elastic stage (72.8%)) (Fig. 8). This indicated that new cracks and failure occurred later in the 30° specimens, which was consistent with the low Young’s modulus and high Poisson’s ratio of the 30° specimens (Table 2).

The stress-strain curves of the two 90° specimens showed special undulations and a strong resistance to damage. The difference was that the 90-1 specimen had a higher crack initiation stress (115.292 MPa) and a longer linear elastic stage (77.48%), while the 90-2 specimen had a lower crack initiation stress (55.336 MPa) and a longer period of stable crack propagation (59.63%). The two specimens at 60° had a weak resistance to failure, and the crack initiation stress (\( \sigma_{ci} \)), critical dilatancy stress (\( \sigma_{cd} \)) and peak stress (\( \sigma_f \)) were all low. Specimen 60-2 had an extremely short unstable crack propagation phase (2.0%), in which the critical dilatancy stress and peak stress were very similar, which indicated that the specimen soon reached its stress limit and failed after the transition from volume compression to volume expansion. The difference between the two 0° specimens was obvious. The 0-2 specimen showed a strong resistance to failure, while the 0-1 specimen showed the opposite. The above analysis of the stress-strain curve showed that the deformation and failure process of rock under stress is very complex. It is not only obviously related to the bedding direction, but also to the initial damage, mineral composition, and other factors.

IV. ULTRASONIC RESPONSE CHARACTERISTICS

The change in the internal pore structure of shale under an external load causes a change in the ultrasonic propagation media, giving rise to changes in the ultrasonic propagation characteristics. If the parent shale is taken as a linear elastomer, its elastic parameters will remain constant under external stresses. In this case, the state of the ultrasonic wave propagating through the shale will primarily rest with the changes in the pores and fractures within the shale, but have no fundamental connection with the stress state of the shale. In the course of ultrasonic dynamic transmission through a loaded shale, the wave velocity information is affected jointly by the size, location, shape, burial depth, and other conditions of the cracks within the shale, producing a complicated coupling process.

A. WAVE VELOCITY

During the test, ultrasonic waveform curves were collected using the acoustic acquisition system. To avoid interference from reflected waves and refracted waves, the waveform in the oscilloscope was adjusted to obtain a clear waveform image. The first wave picks were based on the first breaks estimated from approximately 1% of the first peak amplitude. Then, the test system could automatically calculate the arrival time of the first ultrasonic wave through the specimen (Fig. 9). As a result of the application of uniaxial compression, the specimen height changed during the test. Specifically, \( L_0(1 - \varepsilon_1) \) denotes the actual specimen height (mm), \( L_0 \) denotes the initial specimen height, and \( \varepsilon_1 \) denotes the corresponding strain to the ultrasonic loading time, which can be obtained manually from the test system. The propagation velocity of the acoustic wave through the shale specimen can be calculated using (5):

\[
v_{p,s} = \frac{L_0(1 - \varepsilon_1)}{T - T_0} \tag{5}
\]

where \( v \) denotes the wave velocity, km-s\(^{-1} \); \( v_p \) denotes the P-wave velocity; \( v_s \) denotes the S-wave velocity; \( T \) denotes the first-wave arrival time, \( \mu \text{s} \); and \( T_0 \) denotes the delay time of the electronic circuit, \( \mu \text{s} \).

We can analyze the change in the wave velocity characteristics corresponding to the three phases of crack evolution. Fig. 10 shows the curves of the P-wave and S-wave velocities varying with the axial strain, where the red dashed lines are used to divide the three phases.

1. Linear elasticity phase: S-wave and P-wave velocities both show a steep rising trend. This phase records
FIGURE 6. Axial Stress–axial strain (radial strain, volumetric strain) curves and the characteristic points of shale specimens with different bedding angles.
the linear compression of shales and the gradual closure and size reduction of original cracks after being extruded. In the absence of new stress cracks, the acoustic energy attenuated around the pores, and the acoustic waves directly propagated through some small cracks, resulting in an increasing wave velocity. Before reaching the crack initiation strain (\(\varepsilon_{ci}\)), the P-wave and S-wave velocity curves, especially the latter, showed a few declining jump points, possibly because some of the original cracks in the shale began to initiate along the tip under compressive shear or adjacent original cracks began to interconnect, resulting in an increased original crack size, attenuation of the acoustic energy, and a decrease in the acoustic velocity. Ultrasonic waves are highly sensitive to cracks, and the crack initiation stress obtained from the stress-strain curve may lag.

(2) Stable crack propagation phase: S-wave and P-wave velocities present a gentle rising trend. Specifically, the gentle rising stage of specimen 60-3 was not significant, while that of specimen 30-1 (S-wave velocity) was advanced. In this phase, the original cracks in the shale propagated, and many new cracks formed. The acoustic waves experienced scattering and refraction around the cracks, and the acoustic energy attenuated, resulting in a decrease in the acoustic velocity and the appearance of declining jump points on the curve. However, the shale was further compressed, and the pores and fractures in the shale were flattened. The two-phase changes exerted a common effect on the wave velocity, as was comprehensively manifested by the flat growth in the acoustic velocity.

Unstable crack propagation phase: S-wave and P-wave velocities first rose to the highest point and then dropped rapidly. In this phase, the shale underwent a transition from volume compression to volume expansion, and the cracks gradually propagated, converged, and increased in size, along with a constant scattering and refraction of the acoustic waves and a significant acoustic energy attenuation. All of these factors combined to reduce the wave velocity. The peak wave velocity uniformly occurred before the peak strain (\(\varepsilon_f\)).
and, compared to the P-wave velocity, the S-wave velocity generally declined earlier and at a greater amplitude. This trend was more significant in the case of specimen 30-1. When the axial strain reached 64.1% of the ultimate strain, the S-wave velocity showed a declining inflection point; the P-wave velocity did not begin to decline until the axial strain reached 89.8% of the ultimate strain. In the case of specimen 90-1, the peak points of the P-wave and S-wave velocities overlapped, and the P-wave and S-wave velocities both began to decline when the axial strain reached 96.3% of the ultimate strain.

Given that the propagation velocity of the ultrasonic waves in the shale specimens is primarily affected by crack development, the jump points on the wave velocity curve should be the points where the internal cracks of the specimen change significantly. To further discuss the response relationship between the ultrasonic velocity and crack evolution, we introduce the concept of the fracture volume strain to characterize the change in the fracture volume in the shale. In the shale loading process, the volume strain ($\varepsilon_v$) is the sum of the elastic volume strain ($\varepsilon_{ve}$) and the fracture volume strain ($\varepsilon_{vc}$). In this case, the fracture volume strain can be calculated from (6):

$$\begin{cases} 
\varepsilon_{ve} = \frac{1 - 2PR}{YM} \sigma_1 \\
\varepsilon_{vc} = \varepsilon_v - \varepsilon_{ve} 
\end{cases}$$

(6)

To reflect the dynamic change in the fracture volume, here the elastic modulus and Poisson’s ratio adopt the dynamic values calculated by the ultrasonic velocity.

$$YM_d = \frac{v_p^2 \rho (1 + PR_d)(1 - 2PR_d)}{1 - PR_d}$$

(7)

$$PR_d = \frac{v_p^2 - 2v_s^2}{2(v_p^2 - v_s^2)}$$

(8)

where $\rho$ denotes density, g·cm$^{-3}$; $YM_d$ denotes the dynamic Young’s modulus, KPa, and $PR_d$ denotes the dynamic Poisson’s ratio, %.

Notably, under the above test conditions (the maximum principal stress direction being the same as the transmission direction), the S-wave was more sensitive than the P-wave to the initiation and propagation of cracks, so the following section offers a further analysis of the S-wave only. The curves of the S-wave velocity, volume strain, and fracture volume strain varying with axial strain are shown in Fig. 11. A comparison shows that the corresponding relationships among the jump points in the S-wave velocity, volume strain, and fracture volume strain curves are not ideal. The fracture volume strain curve is relatively flat, different from the obvious fluctuation of the S-wave velocity curve. The changes in the two adjacent points on the curve were analyzed and normalized:

$$\xi_v = \frac{\Delta v}{v_{^*\text{max}} - v_{^*\text{min}}}$$

(9)

where $\xi_v$ denotes the velocity change rate of two adjacent points, %; $v_{^*\text{max}}$ is the maximum velocity in the interval, m·s$^{-1}$; $v_{^*\text{min}}$ is the minimum velocity in the interval, m·s$^{-1}$;
FIGURE 10. Relationships between axial stress–axial strain curves and wave velocity curves of different specimens with 0°, 30°, 60° and 90° bedding angle.
FIGURE 11. Relationships among $v_s$, $\epsilon_v$ and $\epsilon_1$ of shale specimens with different bedding angles.

and $\Delta v$ is the difference between two adjacent velocities, m·s$^{-1}$. The same method can be used to calculate the change rate of the fracture volume strain ($\xi_1$). When the velocity changed greatly, the change in the crack volume strain was not obvious, such as at A ($\xi_v = 0.361$, $\xi_e = 0.078$) and B ($\xi_v = 0.222$, $\xi_e = 0.053$) of the 0-2 specimen. The fracture volume strain and the ultrasonic velocity changed greatly at the same time, such as C for the 60-3 specimen ($\xi_v = 0.310$, $\xi_e = 0.605$) and D for the 90-1 specimen ($\xi_v = 0.049$, $\xi_e = 0.424$). This is because the crack volume strain only reflects the change in the total volume of the crack, but cannot reflect the change in the crack in the individual area of the specimen. Compared with the volume strain of the crack, the wave velocity is more sensitive, and the wave velocity curve fluctuates greatly. The ultrasonic wave penetrates the rock mass, and the changes in the cracks in the rock mass transmission area have an impact on the wave speed. This exactly illustrates the wave speed’s superiority in detecting the change in the crack in the rock. Relying on the obvious jumping points of the ultrasonic velocity curve, we could initially judge the possible key points of the changes in the pores and cracks during the rock failure process.

B. BEDDING DIFFERENCE

The above analysis showed that there were obvious bedding differences in the overall failure mode, stress and wave velocity response of shale. The difference in the influence of the bedding structure on shale deformation and failure may be quantified using the sensitivity of the wave velocity to the internal structure of the rock. The bedding difference index can be calculated by (10).

$$D = \frac{v_{\text{max}} - v_{\text{min}}}{v_{\text{max}}}$$

where $v_{\text{max}}$ and $v_{\text{min}}$ denote the maximum and minimum wave velocity of all ultrasonic transmission velocities at the same time (the same strain), respectively, m·s$^{-1}$.

Fig. 12 shows the curves of the P-wave velocity, the S-wave velocity and the bedding difference index with the axial strain of specimens with different bedding angles. The P-wave velocities were generally higher than the S-wave velocities of the specimens with the same bedding angle. The P-wave velocity was generally between 3000 m·s$^{-1}$ $\sim$ 3600 m·s$^{-1}$ and that of the S-wave was roughly between 1800 m·s$^{-1}$ $\sim$ 2000 m·s$^{-1}$. Among them, the wave velocities of the 60° and 90° specimens were close and significantly higher than those of the 0° and 30° specimens. In the process of uniaxial compression, the difference in the bedding always existed, and the difference index of the bedding calculated by the P-wave was higher. As the uniaxial compression intensified, the bedding difference index calculated from the P-wave velocity and S-wave velocity all showed an overall decreasing trend. This result indicated that the beddings were cut and
destroyed, the friction between the beddings decreased, and the effect of beddings on destruction gradually decreased as the failure of the shale specimen increased.

C. BRITTLENESS EVALUATION

The above analysis of the failure evolution process showed that these samples had an obvious brittleness. Next, we evaluate the brittleness of the shale samples and discuss a new brittleness evaluation method by using an ultrasonic response speed and its applicability. First, the brittleness of shale samples is preliminarily evaluated by mineral content. The percentage of brittle minerals, such as quartz, feldspar and carbonate, is taken as the index to evaluate brittleness:

\[
B_1 = \frac{(W_{qtz} + W_{carb})}{W_{total}} \tag{11}
\]

where \(B_1\) denotes the brittleness index, \(0 \sim 1\). To distinguish the different calculation methods, a subscript was added below (e.g., 1, 2 and 3); \(W_{qtz}\) denotes the total content of feldspar, quartz and muscovite; \(W_{carb}\) denotes the content of carbonate minerals, including dolomite, calcite and other carbonate components; and \(W_{total}\) denotes the total mineral content.

According to (11), the brittleness index of the shale sample was 0.86, which showed that the brittleness of the selected shale sample was very high.

The brittleness of the rock can be evaluated by the relevant mechanical property index [17]. A high Young’s modulus and low Poisson’s ratio are signs of brittleness. The static Young’s modulus (YM) and static Poisson’s ratio (PR) can be calculated according to (3) and (4), respectively. Then, YM and PR are normalized and averaged, and the brittleness index can be expressed as:

\[
YM_{BRIT} = \frac{YM - YM_{cmin}}{YM_{cmax} - YM_{cmin}} \times 100\% \tag{12}
\]

\[
PR_{BRIT} = \frac{PR - PR_{cmax}}{PR_{cmin} - PR_{cmax}} \times 100\% \tag{12}
\]

\[
B_2 = \frac{(YM_{BRIT} + PR_{BRIT})}{2} \tag{12}
\]

where \(YM_{BRIT}\) denotes the normalized Young’s modulus, 10 GPa; \(PR_{BRIT}\) denotes the normalized Poisson’s ratio, %; \(YM_{cmax}\) denotes the regional maximum static Young’s modulus, 10 GPa, set as 10; \(YM_{cmin}\) denotes the regional minimum Young’s modulus, 10 GPa, set as 0; \(PR_{cmax}\) denotes the regional maximum static Poisson’s ratio, set as 0; and \(PR_{cmin}\) denotes the regional minimum Poisson’s ratio, set as 0.4. The value assignments here were given by the statistical data prepared by Liu et al. [24].

Based on the stress-strain curve, extracting the pre-peak or post-peak characteristic values to evaluate the brittleness of rock is the most commonly used method [8] [9]. The post-peak values are prone to deviation, since its measurement is easily affected by experimental operation and equipment. In this paper, the calculation based on the pre-peak characteristic values was used (Table 2). The brittle failure of rock is a process in which the stress reaches the cracking stress to produce cracks and develop gradually. The rock brittleness index is directly proportional to the difference between the crack initiation stress and the peak stress, which can be expressed as:

\[
B_2 = \frac{(\sigma_f - \sigma_{ci})}{(\epsilon_f - \epsilon_{ci})} \tag{13}
\]

Similar to the above stress-strain curve method, using the sensitive response of an ultrasonic velocity to rock failure, the brittleness of rock can be calculated from the characteristic response velocities. According to the above ultrasonic response velocity analysis, with an increase in the axial compression, there is a jumping point of the first velocity reduction in the ultrasonic velocity curve, which can be used as the rock cracking response velocity \(v_{ci}\), and there is a peak point of the response velocity \(v_f\) before the continuous decrease in the velocity (Table 3, subscript “p” for the P-wave and subscript “s” for the S-wave, etc.). Since the ultrasonic response speed does not start from “0”, the speed when the stress is “0” is taken as the initial response speed.
TABLE 2. Mechanical parameters and characteristic stresses and strains of shale specimens.

| Specimen label | YM /GPa | PR% | σci/MPa | εci/% | σbf/MPa | εbf/% | σf/MPa | εf/% |
|---|---|---|---|---|---|---|---|---|
| 0-1 | 25.746 | 0.149 | 58.647 | 0.2510 | 90.776 | 0.3741 | 129.453 | 0.5207 |
| 0-2 | 22.751 | 0.341 | 111.382 | 0.4362 | 128.742 | 0.5205 | 153.354 | 0.6601 |
| 30-1 | 18.724 | 0.274 | 105.312 | 0.5596 | 135.649 | 0.7403 | 159.467 | 0.9359 |
| 30-3 | 18.752 | 0.309 | 123.79 | 0.6693 | 145.184 | 0.8071 | 155.304 | 0.9123 |
| 60-2 | 25.746 | 0.155 | 86.476 | 0.3152 | 128.241 | 0.4765 | 130.86 | 0.4957 |
| 60-3 | 27.487 | 0.196 | 65.381 | 0.2769 | 90.776 | 0.3741 | 129.453 | 0.5207 |
| 90-1 | 23.093 | 0.136 | 115.292 | 0.6475 | 136.221 | 0.7880 | 148.804 | 0.9341 |
| 90-2 | 24.236 | 0.143 | 55.336 | 0.2627 | 147.555 | 0.7666 | 154.651 | 0.7435 |

TABLE 3. Characteristic response velocities and strains of shale specimens.

| Specimen label | v0p/(km·s⁻¹) | ε0p/% | vbf/(km·s⁻¹) | εbf/% | vbf/(km·s⁻¹) | εbf/% | vbf/(km·s⁻¹) | εbf/% |
|---|---|---|---|---|---|---|---|---|
| 0-2 | 3255 | 0.6001 | 1902 | 0.6001 | 3134 | 0.1801 | 1866 | 0.0902 |
| 0-1 | 3240 | 0.5101 | 1885 | 0.4201 | 3150 | 0.2102 | 1875 | 0.2401 |
| 30-1 | 3253 | 0.8408 | 1910 | 0.6002 | 3141 | 0.3602 | 1861 | 0.0901 |
| 30-3 | 3268 | 0.8395 | 1914 | 0.7798 | 3149 | 0.3296 | 1884 | 0.2098 |
| 60-2 | 3486 | 0.4201 | 2049 | 0.3904 | 3376 | 0.0601 | 2027 | 0.0601 |
| 60-1 | 3482 | 0.4199 | 2045 | 0.4504 | 3449 | 0.3297 | 2026 | 0.1197 |
| 90-1 | 3511 | 0.8995 | 2066 | 0.8995 | 3397 | 0.1792 | 2025 | 0.1193 |
| 90-2 | 3539 | 0.7202 | 2066 | 0.6601 | 3384 | 0.1201 | 2049 | 0.0603 |

of the interval. The brittleness index can be expressed as:

\[ B_3 = \frac{(v_f - v_{ci})/(v_f - v_0)}{\epsilon_{f,v} - \epsilon_{ci,v}} \]  

(14)

where \( v_0 \) denotes the initial response speed, m·s⁻¹; \( \epsilon_{ci,v}, \epsilon_{f,v} \) and \( \epsilon_0 \) denote the axial strain corresponding to \( v_{ci}, v_f \) and \( v_0 \) respectively, %.

The brittleness indices of the shale samples were calculated by (12), (13) and (14), and two specimens were taken from the same bedding angle (Fig. 13). There was no comparability between the brittleness index values obtained by the different calculation methods. \( B_1 \) showed that the two 30° specimens were the most brittle, while the other three calculation methods showed that the two 30° specimens were less brittle. Based on the above analysis of the failure process and the failure mode, although the broken surface of the 30° specimens was relatively obvious (Fig. 5), cracks and failures occurred later (Fig. 7), and the proportion of the crack propagation stage was not high (Fig. 8), so the brittleness of the 30° specimens should be relatively poor. It can be seen that \( B_1 \) was quite different from the actual situation, and the applicability was poor. \( B_2, B_{3,p}, \) and \( B_{3,s} \) all showed certain applicability, and the results were consistent on some specimens, such as specimen 90-2 and specimen 60-2, which all showed a higher brittleness, and specimen 30-1 and specimen 30-3, which all realized poor brittleness. However, the individual specimens showed obvious differences; for example, \( B_2 \) of the 0-1 specimen was higher, while \( B_{3,p} \) and \( B_{3,s} \) were lower, \( B_2 \) and \( B_{3,s} \) of the 90-1 specimen were lower, and \( B_{3,p} \) was higher. Sometimes the \( B_2 \) and \( B_{3,s} \) values of two specimens with the same bedding angle differed greatly, but the \( B_{3,p} \) values were relatively close.
V. CONCLUSION

In this study, a dynamic ultrasonic transmission test was performed on Longmaxi Formation shale specimens with varying bedding angles under uniaxial compression. The dynamic mechanical and ultrasonic responses of the specimens under compression were collected, and the failure evolution characteristics were analyzed.

Ultrasonic waves are very sensitive to crack changes in shales. With an increasing uniaxial stress, both the P-wave velocity and S-wave velocity showed phased changes, including a rapid increase, a slow increase, and a rapid drop after reaching the highest point. The apparent jump point on the wave velocity curve is exactly the time when pores and fractures in the shale may experience a substantial change. This method can be used to preliminarily determine the critical points in the crack initiation and propagation in shales during failure evolution.

From the view of the uniaxial compression failure process, failure forms and ultrasonic response velocity characteristics, the bedding angle had a significant impact on the shale failing. Bedding planes could, to a large extent, explain the differences in the macroscopic mechanical properties and the failure modes of shales. The difference index of bedding using ultrasonic velocity was calculated to evaluate the influence of the bedding angle on the shale failure process. The results showed that a difference in the bedding always existed in the process of uniaxial compression, and the difference index of the bedding calculated by the P-wave was higher. As the uniaxial compression intensified, the bedding difference index calculated from the P-wave velocity and the S-wave velocity all showed an overall decreasing trend, and the effect of bedding on the destruction gradually decreased.

It was very obvious that the selected Longmaxi Formation shale specimens showed significant brittleness characteristics. Using the sensitivity of the ultrasonic velocity to the internal structure of rock, a method for calculating the rock brittleness index based on the ultrasonic response velocity was proposed. Compared with the mechanical property index method and the stress-strain curve method, the ultrasonic response velocity method revealed a good applicability.

REFERENCES

[1] E. A. Kaarsberg, “Introductory studies of natural and artificial argillaceous aggregates by sound-propagation and X-ray diffraction methods,” J. Geol., vol. 67, no. 4, pp. 447–472, Jul. 1959.
[2] B. Ran, S. G. Liu, and W. Sun, “Lithofacies classification of shales of the lower paleozoic wufeng-longmaxi formation in the sichuan basin and its surrounding areas,” China, Earth Sci. Frontiers, vol. 23, no. 2, pp. 96–107, Mar. 2016.
[3] C. M. Sayers, “Inversion of ultrasonic wave measurements to obtain the microcrack orientation distribution function in rocks,” Ultrasonics, vol. 26, no. 2, pp. 73–77, Mar. 1988.
[4] C. Y. Jia, A. L. Jia, and P. L. Han, “Reservoir characteristics and development evaluation of organic-rich gas-bearing shale layer in the Low Silurian Longmaxi Formation Si-Chuan basin,” Natural Gas Geosci., vol. 28, no. 9, pp. 1406–1415, Sep. 2017.
[5] D. F. Winterstein and B. N. P. Paulsson, “Velocity anisotropy in shale determined from crosbole seismic and vertical seismic profile data,” Geophysics, vol. 55, no. 4, pp. 470–479, Apr. 1990.
[6] D. N. Dewhurst, A. F. Siggins, J. Sarout, M. D. Raven, and H. M. Nordgard-Bolås, “Geomechanical and ultrasonic characterization of a norwegian sea shale,” Geophysics, vol. 76, no. 3, pp. WA101–WA111, May 2011.
[7] F. L. Xu, Q. Cheng, and H. L. Zhu, “Response analysis of shale bedding structure to ultrasonic characteristics and its application,” Petroleum Explor. Develop., vol. 46, no. 01, pp. 82–91, Feb. 2019.
[8] G. Q. Chen, C. Zhao, and T. Wei, “Evaluation method of brittle characteristics of rock based on full stress-strain curve and crack initiation stress,” Chin. J. Rock Mech. Eng., vol. 37, no. 1, pp. 51–59, Jan. 2018.
[9] H. Zhou, F. Z. Meng, and C. Q. Zhang, “Quantitative evaluation of rock brittleness based on stress-strain curve,” Chin. J. Rock Mech. Eng., vol. 33, no. 6, pp. 1114–1122, Jun. 2014.
[10] J. Deng, S. Wang, and D. H. Han, “The velocity and attenuation anisotropy of shale at ultrasonic frequency,” J. Geophys. Eng., vol. 6, no. 3, pp. 269–278, Sep. 2009.
[11] J. Xiong, L. X. Liang, and X. J. Liu, “Experimental study on acoustic penetration through the longmaxi formation shale rock in South region of Sichuan basin,” Chin. J. Underground Space Eng., vol. 10, no. 5, pp. 1071–1077, Oct. 2014.
[12] J. E. White, L. Martineau-Nicoletis, and C. Monash, “Measured anisotropy in pumice shale,” Geophys. Prospecting, vol. 31, no. 5, pp. 709–725, Oct. 1983.
[13] L. Vernik and A. Nur, “Ultrasonic velocity and anisotropy of hydrocarbon source rocks,” Geophysics, vol. 57, no. 5, pp. 727–735, May 1992.
[14] P. L. Swanson and H. Spetzler, “Ultrasonic probing of the fracture process zone in rock using surface waves,” Mech. Productiv. Protection, vol. 22, no. 6, pp. 67–76, 1984.
[15] P. Zhang, C. H. Yang, H. Wang, Y. T. Guo, F. Xu, and Z. K. Hou, “Stress-strain characteristics and anisotropy energy of shale under uniaxial compression,” Rock Soil Mech., vol. 39, no. 6, pp. 2016–2025, Jun. 2018.
[16] P. Zhang, C. H. Yang, and H. Wang, “Stress-strain characteristics and anisotropy energy of shale under uniaxial compression,” Rock Soil Mech., vol. 39, no. 6, pp. 2106–2114, 2018.
[17] Q. H. Li, M. Chen, and Y. Jin, “Indoor evaluation method for shale brittleness and improvement,” Chin. J. Rock Mech. Eng., vol. 31, no. 8, pp. 1680–1685, Aug. 2012.
[18] R. E. Thill, T. R. Bar, and R. C. Steckley, “Velocity anisotropy in dry and saturated rock spherics and its relation to rock fabric,” Int. J. Rock Mech. Mining Sci. Geomechanics Abstr., vol. 10, no. 6, pp. 535–557, Nov. 1973.
[19] T. Lo, K. B. Coyner, and M. N. Toksoz, “Experimental determination of elastic anisotropy of berea sandstone, chiecopee shale, and chelsmford granite,” Geophysics, vol. 51, no. 1, pp. 164–171, Jan. 1986.
[20] U. Kula, D. N. Dewhurst, A. F. Siggins, and M. D. Raven, “Stress anisotropy and velocity anisotropy in low porosity shale,” Tectonophysics, vol. 503, nos. 1–2, pp. 34–44, Apr. 2011.
[21] Y. Wang, C. H. Li, Y. Z. Hu, and T. Q. Mao, “Laboratory investigation of hydraulic fracture propagation using real-time ultrasonic measurement in shale formations with random natural fractures,” Environ, Earth Sci., vol. 76, no. 22, p. 768, Nov. 2017.
[22] Z. Deng, L. J. Cheng, and L. H. Pan, “Influence of bedding dip angle on triaxial stress-strain test and P-wave velocity of shale,” J. Northeast Petroleum Univ., vol. 40, no. 1, pp. 33–39, Feb. 2016.
[23] Z. Q. Lu, X. Q. Hai, J. X. Wei, and R. M. Bao, “Characterizing of oil shale pyrolysis process with laser ultrasonic detection,” Energy Fuels, vol. 30, no. 9, pp. 7236–7240, Sep. 2016.
[24] Z. S. Liu and Z. D. Sun, “New brittleness indexes and their application in shale/clay gas reservoir prediction,” Petroleum Explor. Develop., vol. 42, no. 1, pp. 15–16, Feb. 2015.
YONGLI ZHANG received the Ph.D. degree in mining engineering from Liaoning Technical University, in 2000. He is currently a Professor and a Supervisor for Ph.D. students with the School of Mechanics and Engineering, Liaoning Technical University. He is also the Director of Fund Management Office, Liaoning Technical University. His research interests include mining disaster mechanics, gas mining, and the theory and application of two-phase fluid.

XINLE YANG received the Ph.D. degree in engineering mechanic from Liaoning Technical University, in 2009. From 2016 to 2017, he was a Visiting Scholar with the Department of Industrial Engineering, University of Padova, Italy. He is currently a Professor and a Supervisor for Ph.D. students with the School of Mechanical Engineering, Liaoning Technical University. His research interests include recovery and power generation in low grade heat source and mining of CBM with thermal stimulation.

CHA NG SU received the master’s degree in control theory and control engineering from Liaoning Technical University, in 2007, where she is currently pursuing the Ph.D. degree with the School of Mechanics and Engineering. She is also a Lecturer with the School of Mechanical Engineering, Liaoning Technical University. Her research interests include the mining of CBM with thermal stimulation and intelligent control.