Experimental study on anisotropic strength properties of sandstone

X. M. Zhang, J. S. Yang & B. C. Liu
School of Civil Engineering and Architecture, Central South University, Changsha, China

ABSTRACT

A series of uniaxial and triaxial tests are conducted on core samples of sandstone from Hunan highway region in China. The influence of the inherent anisotropy of sandstone on the mechanical characteristics, including the failure mode, failure strength and residual strength, has been investigated. The experimental results show that the tested sandstone represents the low anisotropy, and failure mode, peak failure strength and residual strength under different confining pressures is directly related to the inclination angle of specimen foliation with respect to the horizontal direction. Analyzing the experimental data on the basis of the Mohr-Coulomb failure criterion, the brittle-ductile transition properties under different loading orientations are brought out, and the relevant brittle-ductile transition confining pressure are predicted by failure criterion. The results show that the existence of oriented bedding planes has a strong influence on the brittle-ductile transition confining pressure.
Key words: anisotropy, failure strength, residual strength, failure mode, brittle-ductile transition, sedimentary sandstone

1 INTRODUCTION

Many rocks exposed near the Earth's surface show well defined fabric elements in the form of bedding, stratification, layering, foliation, fissuring or jointing. In general, these rocks have properties that vary with direction and are said to be inherently anisotropic (Amadei 1996). For example, metamorphic and sedimentary rocks are characterized by inherent or structural anisotropy. Foliated metamorphic rocks (e.g., slate, phyllite, schist, and gneiss) with textures showing the parallel orientation of mineral grains tend to split or break along the foliation or cleavage planes, rather than across the planes or at other orientations. Non-foliated metamorphic rocks such as marble also show some anisotropy. Some stratified or bedded sedimentary rocks (e.g., shale, sandstones) possess closely spaced laminations that appear to have a strong directionality (Tien, et al. 2006). Anisotropy of these rocks is dependent on the sampling orientation with respect to loading directions (Goodman 1993). And the influence of the intrinsic anisotropy on failure strength is one of the basic data required for predicting rock performance for a variety of surface and underground structures. Therefore, the design and stability analysis of underground structures located in anisotropic rocks require estimating the variation of strength and deformation behaviors and analyzing the failure mechanisms of anisotropic rocks with the orientation of stress.

Rock anisotropy is a well-known behavior and is of considerable interest in the field of rock mechanics and engineering over the past several decades. Many scholars have devoted considerable efforts to the study of rock anisotropy. Much research has been carried out, including experimental characterization (Nova 1980; Niandou et al. 1997; Tien et al. 2000; Nasseri et al 2003; etc.), theoretical studies and numerical modelling (Duveau et al. 1998; Pietruszczak et al. 2002; etc.). All the results obtained have shown that the rock strength varies with the loading orientation, and the shape of the curve of compression strength and the orientation angle are the most common representation of the nature of strength anisotropy.

In this paper, anisotropic strength behaviour of the sandstone form Hunan highway area in China has been brought out through the testing of specimens with the oriented weakness planes under uniaxial and triaxial conditions. The influence of the inherent anisotropy (transversely isotropy) on the mechanical characteristics was investigated, specially the brittle-ductile transition properties in different loading orientations.

2 PRESENTATION OF TESTS

Sandstone blocks used in present work were taken from the tunnel face of Queerxi tunnel, one of Changji freeway tunnel group in Hunan province, China, where the rocks reveals horizontal deposits. Then, oriented samples were prepared using cores obtained from the blocks. All samples were carefully examined to make sure that they were truly intact. As shown in Fig.1, about 100 standard cylindrical specimens of 50 mm in diameter and 100 mm in height were prepared at different loading orientations of 0°, 22.5°, 45°, 67.5° and 90° with respect to the horizontal orientation illustrated in Fig.2.

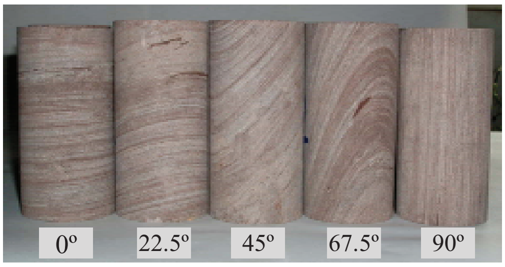

Fig.1 sandstone specimens cored at different orientations

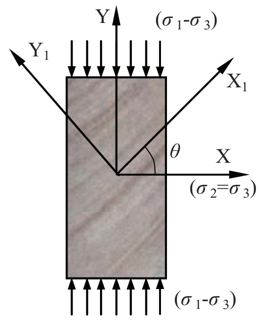

Fig.2 Definition of loading orientation

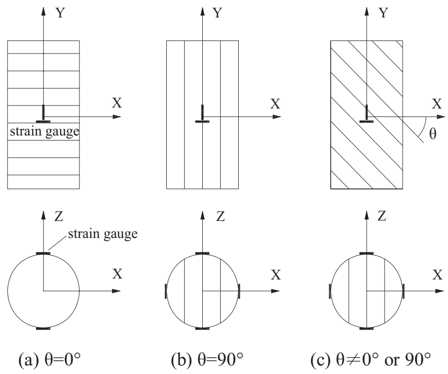

Fig.3 Positions of strain gauges in triaxial compression test

Strains of samples were measured by means of strain gauges pasted on the surface shown in Fig.3. Two gauges are oriented in the axial loading direction, which allow one to measure the longitudinal strains of the sample. Two pairs of strain gauges are respectively oriented in the direction parallel or perpendicular to the bedding planes. These measure the transversal strains which are parallel or perpendicular to the bedding planes. A series of uniaxial and triaxial tests were conducted with confining pressures of 0, 20, 40 and 60MPa on MTS mode 815 stiffness rock testing machine according to the ISRM suggested standards.

3 TEST RESULTS AND DISCUSSION

3.1 Complete stress-strain curve

The complete stress-strain curves for various orientations and confining pressure are obtained, and the significant results are presented from these tests as shown in Fig.4. From the stress-strain curves in Fig.4, it can be seen that the mechanical properties of sandstone with varying orientation angle are obviously different under same confining pressure. The segment of curves before the peak stress point represents the linear elasticity, and the samples appear clear brittle failure after peak point in uniaxial and lower confining pressures. With the increase of confining pressure, deformation tends to represent the transition from brittle to ductile near and after the peak point, and some samples have visible strain hardening.

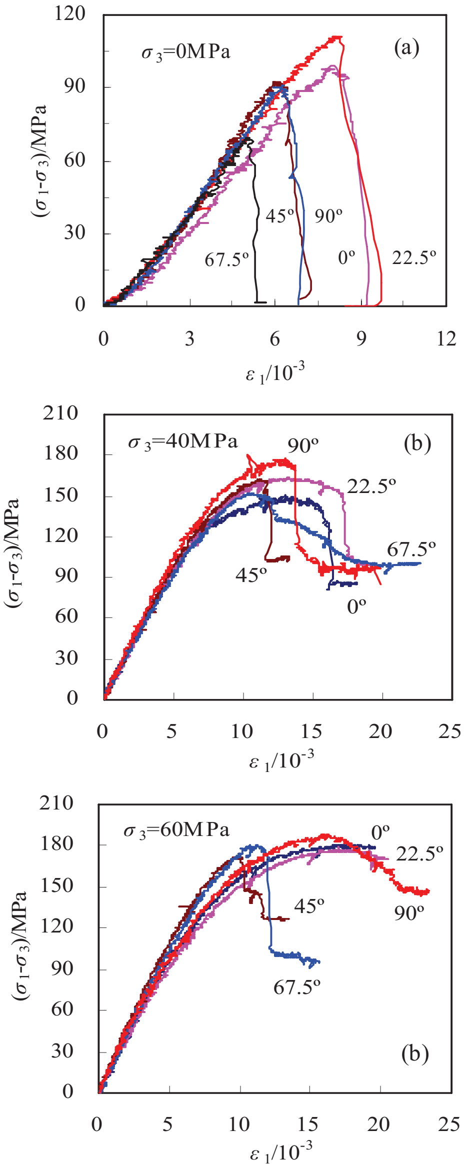

Fig.4 complete stress-strain curves of sandstone samples with different orientation angle

3.2 Strength behavior in uniaxial and triaxial condition

In order to investigate the influence of sedimentary weakness planes on failure strength of sandstone samples, the varying law between the uniaxial failure stress and the corresponding orientation is presented in Fig.5, including the average experimental data obtained from three to five tests for each orientation. And the varying curves of the triaxial failure strength with different confining pressure and orientation are shown in Fig.6.

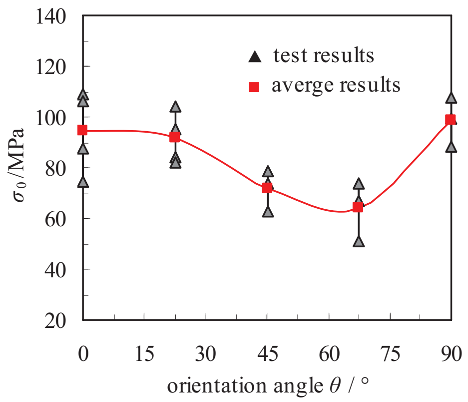

Fig.5 Variation of uniaxial peak strength in loading orientation

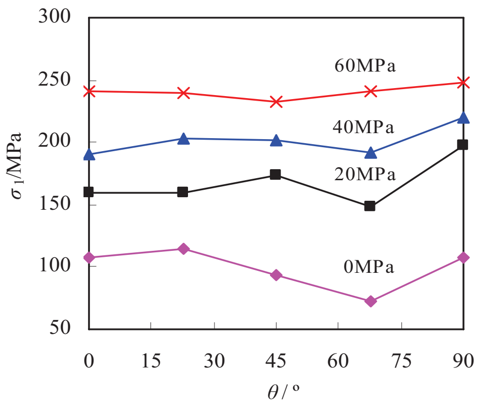

Fig.6 Evolution of peak stress in loading orientation with various confining pressure

The failure strength, generally defined at the peak point of complete stress-strain curves in uniaxial and triaxial tests, has been obviously influenced due to the existence of bedding planes and varies with the loading orientation for all confining pressures. The maximum strengths are found when the axial compressive stress is nearly normal or parallel to bedding planes. The minimum strength is obtained when the angle between the horizontal orientation and bedding plane is 67.5°. The shape of the curves is asymmetrical shoulder-type as shown in Fig.5 and 6.

The values of failure strength at different loading orientation gradually become nearly equal with the increase of the confining pressures. So the orientation angle gradually has little effect on the peak strength under higher confining pressure. The degree of strength anisotropy, which commonly quantified by the ratio between the maximum and minimum values of failure strength for a given confining pressure, is calculated by:

$$R_c = \sigma_{ci(90)} / \sigma_{ci(\min)} \tag{1}$$

Variations of the strength anisotropy with confining pressure are shown in Fig.7. The value of R_c continuously decreases with confining pressure. According to a review study by Ramamurthy (1993), the tested sandstone represents low strength anisotropy. The maximum value is 1.49 in uniaxial compression test. In triaxial tests with relatively higher confining pressure σ_3=60 MPa, the degree of strength anisotropy for the sandstone decreases 1.1, nearly equal to the isotropic rocks. This property of the rocks similar to sandstone is different from many ductile sedimentary rocks with strong anisotropy, like shale (Niandou et al. 1997) and schist (Duveau et al. 1998), which the effect of the confining pressure to reduce the strength anisotropy of rock is small and the strength anisotropy tend towards a constant value greater than 1.

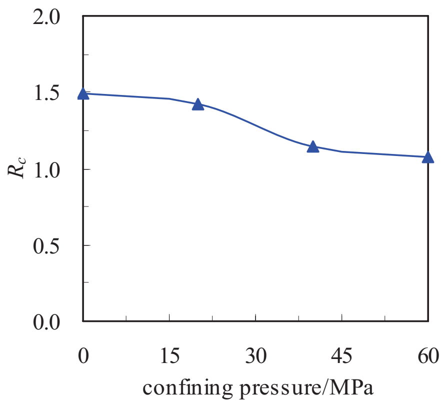

Fig.7 Curve of anisotropy ratio with various confining pressure

Otherwise, the experimental results show the fact that the triaxial residual strength is directly related to the confining pressure and the inclination angle of specimen foliation with respect to the horizontal direction. The minimum residual strength occurs in the specimen with 67.5 degrees of inclination angle, and specimens with 0 degrees or 90 degrees inclination have maximum triaxial residual strength.

3.3 Failure modes of transversely isotropic sandstone

Failure mode is very important to understand the failure mechanism and deformation properties, and some scholars have summarized the failure mode of transversely isotropic rock (Niandou et al. 1997; Tien et al. 2000; Nasseri et al 2003; etc.).

Direct observations of sample failure surfaces were performed in each compression test as shown in Fig.8. These observations have shown complex failure modes of sandstone, strongly depending on the loading orientation and confining pressure. The sample failure generally takes place by sliding of bedding planes, shearing of rock matrix or a mixed mode of splitting of bedding planes and shearing of sandstone matrix. The failure occurs in a brittle way under low confining pressures, yielding a sudden collapse of sandstone strength. But along with the increase of the confining pressure, the failure mode of some samples tends to occur in a ductile way.

Fig.8 Failure mode in different loading orientation with various confining pressure

4 BRITTLE-DUCTILE TRANSITION PROPERTY

The properties of the brittle-ductile transition of the rock are important to understand the deformation relating to the confining pressure. Basis on the Mohr-Coulomb failure criterion, the relation between the peak strength and confining pressure, especially the post-peak residual strength and the brittle-ductile transition properties is investigated.

The Mohr-Coulomb strength criterion is one of the most widely used strength criteria in geotechnical engineering application, including in rock engineering modeling and design. The M-C criterion is appropriate to describe the failure process of rocks, especially for the brittle rocks. It yields the following equations:

$$\tau = c + \sigma \tan\phi \tag{2}$$

Where c is the cohesion, σ is the normal stress acting on failure plane, and ϕ is the angle of internal friction.

The criterion is also expressed with major principal stress in the following form:

$$(\sigma_1 - \sigma_3) = 2c\cos\phi + (\sigma_1 + \sigma_3)\sin\phi \tag{3}$$

or

$$\sigma_1 = \frac{1+\sin\phi}{1-\sin\phi}\sigma_3 + \frac{2c\cos\phi}{1-\sin\phi} = k\sigma_3 + l \tag{4}$$

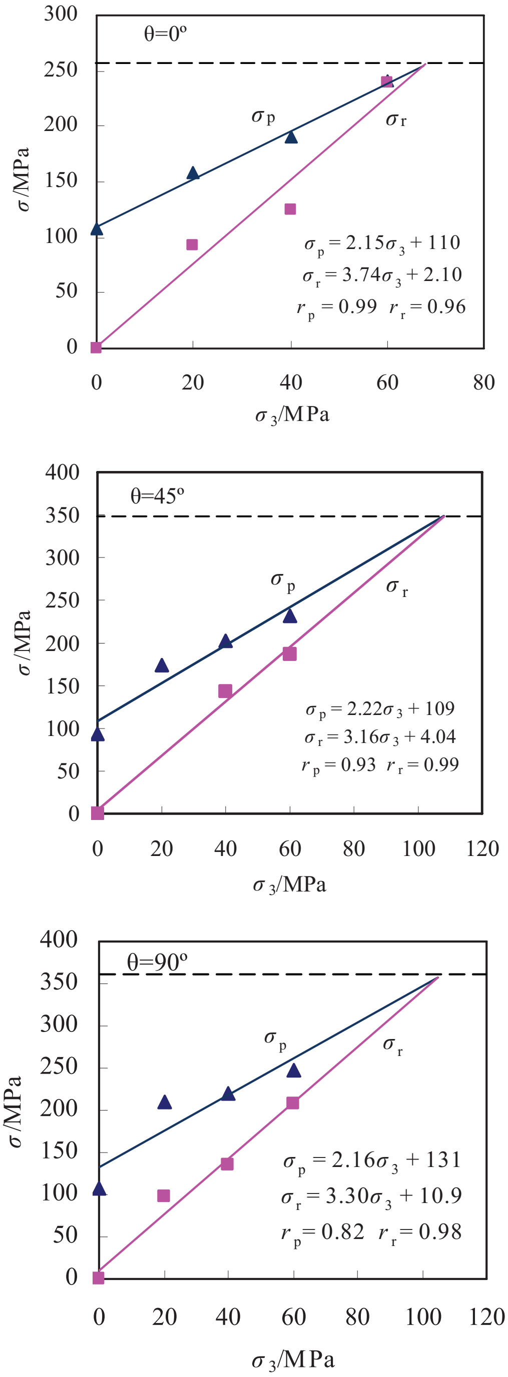

Fig.9 Confining pressure of brittle-ductile transition in various loading orientation

The peak failure strength and post-peak residual strength of sandstone samples are assumed to yield the Mohr-Coulomb failure criterion, and then the parameters k and l can be obtained by the regression analysis method according to the experimental data, as illustrated in Fig.9.

By basis of the equation (4), the curves of the peak failure strength and residual strength with varying confining pressure should intersect at one point. The intersectant point is defined as the starting point of brittle-ductile transition, and then corresponding brittle-ductile transition confining pressures are predicted by the data under lower confining pressures. The results in different loading orientation are presented in Fig.10. It shows that the existence of oriented bedding planes has a strong influence on the brittle-ductile transition confining pressure.

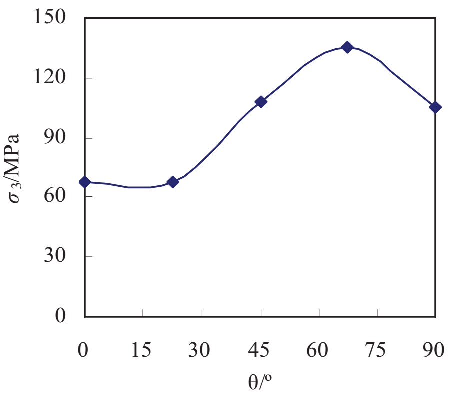

Fig. 10 influence of oriented weak planes on the brittle-ductile transition confining pressure

5 CONCLUSIONS

The experimental results of sandstone samples including the uniaxial and triaxial compression tests under different confining pressure and loading orientation angle have been presented. The tested sandstone represents the low anisotropy, but the influence of the stratification bedding on the mechanical characteristics, including failure mode, brittle-ductile transition confining pressure, is very visible. The experimental study of anisotropic strength properties of sandstone material in this paper will give a better overall understanding of the mechanical behaviors of anisotropic rocks, and their influences on the rock engineering.

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