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Diffuse and localized deformation of a porous Vosges sandstone in true triaxial conditions

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Abstract.

This work presents an experimental study on the diffuse and localized deformation mechanisms of a high porosity (20%) Vosges sandstone (Eastern France) subjected to different stress paths, orthogonal to the initially isotropic state. The experimental campaign was performed using a high pressure true triaxial apparatus (TTA) in which the three principal stresses are independently controlled. A series of 10 quasi-static, monotonous loading tests was performed at two constant mean stress, in the brittle-ductile transition regime, and at five prescribed Lode angles, from axisymmetric compression (ASC) to axisymmetric extension (ASE), as a measure of the deformation mode. The failure surface in each deviatoric plane and changes in macroscopic measurements, such as dilatancy and deformation band angles, tracked by full field digital image correlation technology, indicate a clear effect of the Lode angle on a transition between the brittle and ductile regime, independent from the total mean stress level.

1 Introduction

It is of clear interested in rock mechanics to identify deformation mechanisms which can lead to global failure of a confined rock mass. In porous sandstone, a predominant and well-studied mechanism leading to failure is the development of shear localization in planar bands of finite thickness. Localization patterns involving single or conjugated shear bands have been observed in stressed rock formations in the field [1], as well as in in laboratory settings [2] important and seminal work on localization]. In these controlled and monitored environment, it is possible to reproduce various field conditions and study their influence on shear bands development.

In this context, experimental studies exploring the effect of mechanical loading paths on shear localization is of importance in the field of applied rock mechanics. However, previous laboratory studies observing the effect of stress on the deformation and strength of rock specimens have been, for the most part, performed using conventional triaxial systems [3], limiting the possibility of stress paths to ones where two of the principal stresses have to be equal. It results that models describing the intrinsic behavior of cohesive geomaterials rely heavily on experimental data which typically follow axisymmetric conditions, leaving a broad spectrum of the deviatoric plane unexplored.

Following the seminal work of Mogi [4], experimental equipment which enables independent control of the three principal stresses ($\sigma_1 \geq \sigma_2 \geq \sigma_3 \geq 0$), so called true-triaxial appartatus (TTA), have been designed to ac-

cess all possible stress states in the principal directions, within the allowable pressure range of the system. This type of apparatus has been used in the past for polyaxial compression tests to measure the effect of the intermediate principal stress on rocks with various mineral composition (e.g. [4–7]). More recently, a study by Ingraham et al. [8] investigates the independent effect of stress invariants on the mechanical response of a porous sandstone in a series of independant loading paths on the deviatoric plane. Ma et al. [9] have also followed a similar methodology, exploring the effect of the Lode angle at constant minor principal stress in two porous sandstones. These research have consistently shown a measurable effect of the Lode angle on failure and the development of post-mortem localization patterns. However, experimental data on the subject remains scares.

This article proposes to further study the phenomenon of strain localization under polyaxial stress conditions through a series of TTA experiments, with imposed constrains on the stress invariants. In addition to the analysis of global mechanical and deformation measurements, the design of the testing apparatus made it possible to follow the evolution of strain localization using full field analysis of the kinematics, at the mesoscale, during the deviatoric loading phase.

2 Material and Methods

2.1 Sample characterization

The selected material is a red Vosges sandstone retrieved from the Woustwiller quarry, Eastern France. Its physical characteristics were reported in previous experimental

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Table 1. Mineral characterization of Vosges Sandstone [10]

mineral composition	93% quartz 5% microcline 2% mica and kaolinite
porosity	21%
grain size	150-450 μm
mean grain size	300 μm

campaigns exploring localization in soft porous sandstone under axisymmetric [10] and plane strain [11] loading conditions. Other studies on sandstone from the same Triassic rock formation in the Vosges region suggest a weak mechanical anisotropy in this type of bedded sedimentary rocks [12]. The focus of this study is on a single material orientation of 90° (horizontal bedding).

The arithmetic mean of connected porosity, measured on each sample by progressive vacuum water saturation, was $21\% \pm 1$. It is similar to what was previously recorded for specimens of the same excavated material.

2.2 True Triaxial Apparatus (TTA)

The TTA used in the scope of this work has been developed at laboratoire 3SR to test rock specimen in biaxial and polyaxial loading conditions [14]. It can accommodate machined prismatic samples of $50 \times 30 \times 25 \text{ mm}^3$ inside a specially fabricated urethane membrane (figure 1). The apparatus was designed to apply isotropic confinement of up to 100 MPa, by increasing the cell pressure in which the isolated specimen is located. The stress deviators, in the major and intermediate principal stress directions, are applied by the means of hydraulic pistons in contact with the sample surface. For the specified sample dimensions, deviatoric stresses can reach approximately 500 MPa in both directions.

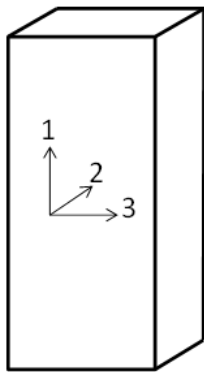


Figure 1. Prismatic specimen deformed in the true triaxial apparatus, with the associated spatial directions

In the intermediate direction, the TTA is equipped with a sapphire view-port enabling the acquisition of images. The digital apparatus Nikon800E with 36 MPx allows a resolution of 7 microns/pixel; with current setting for noise and vibration reduction, photographs can be taken at a regular time interval as fast as 1 every 3 seconds. To perform

incremental digital image correlation (DIC) on the set of recorded images, a fine monochromatic speckle is applied on the sample surface visible through the sapphire view-port. This enables full-field deformation measurements in the major and minor directions. In the out of plane intermediate direction, strain gauges are used to measure deformation in the center of the specimen.

2.3 Loading procedure

In the series of experiments on 10 identically prepared samples, the first and third invariants of the stress tensor remained constant during the deviatoric loading phase. We define these invariants, in terms of principal stresses, as follow:

$$\begin{aligned}\sigma_m &= \frac{1}{3}[\sigma_1 + \sigma_2 + \sigma_3] \\ \tau_{oct} &= \frac{1}{3}[(\sigma_1 - \sigma_2)^2 + (\sigma_1 - \sigma_3)^2 + (\sigma_2 - \sigma_3)^2]^{1/2} \\ \theta &= \arctan \left[\sqrt{3} \frac{\sigma_2 - \sigma_3}{(\sigma_1 - \sigma_2) + (\sigma_1 - \sigma_3)} \right]\end{aligned}\quad (1)$$

where σ_m is the mean stress; τ_{oct} is the octahedral stress which measures the stress departure from the isotropic state; and θ is the Lode angle in the deviatoric plane. It spans from 0° in axisymmetric compression (ASC) to 60° in axisymmetric extension (ASE).

A consistent procedure was followed during the loading phase of each experiment: once the sample is installed and the apparatus assembled, an alignment phase is initiated to insure good contact between the hard platens, loaded by the hydraulic pistons, and the specimens; a subsequent isotropic loading phase consists of increasing the cell pressure, at a rate of 2 MPa/min until the desired mean stress is reached; finally the deviatoric loading phase consist of monotonically increasing the octahedral stress, resolved on the integral of the specimen boundary, by controlling the intermediate and minor principal stresses as functions of the major principal stress. This procedure, regulated by a PID controller, insures the mean stress and Lode angle remained constant for the remaining of the loading phase.

3 Experimental Results

Guided by the study of Bésuelle et al. [10] in which axisymmetric compression loading tests were performed on Vosges sandstone, the range of mean stress was selected so as to reproduce a behavior at failure associated with the brittle-ductile transition regime. The experimental campaign consisted of testing 10 Vosges sandstone specimens at five Lode angles ($0, 15, 30, 45$ and 60°) at the two constant mean stresses of 60 and 90 MPa.

The resulting octahedral stress-strain and volumetric curves, shown in Figure 2, were corrected using displacement measurements from DIC at the sample boundary in directions 1 and 3, while strain gauges are used in direction 2. The comparison of mechanical curves indicates

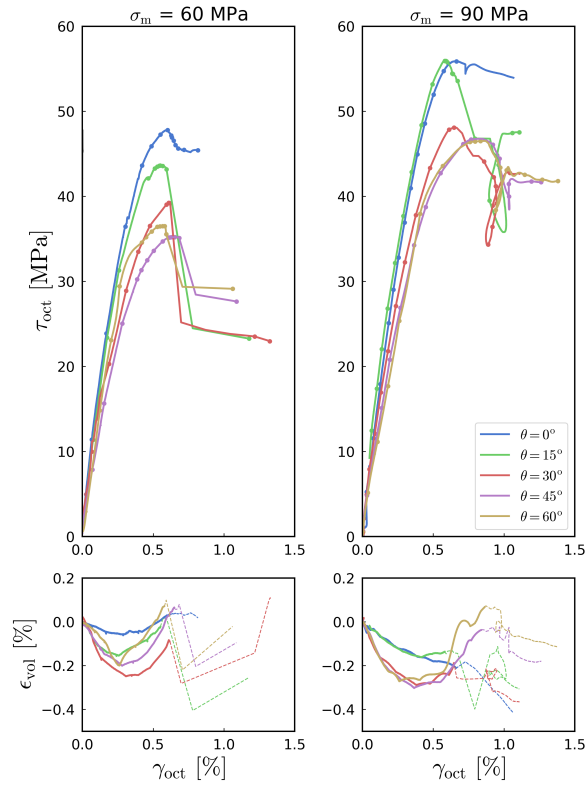


Figure 2. Stress-strain and volumetric curves as a function of octahedral shear stress (γ_{oct}), analogue to τ_{oct} . The dashed lines shows volumetric strains in the post peak regime

that, irrespective of the Lode angle, the increase in mean stress from 60 MPa to 90 MPa induces an increase in the peak strength of the material: a 22% increase for a Lode angle of 0° was measured and a more pronounced increase, greater than 30%, at higher Lode angles (see figure 3a).

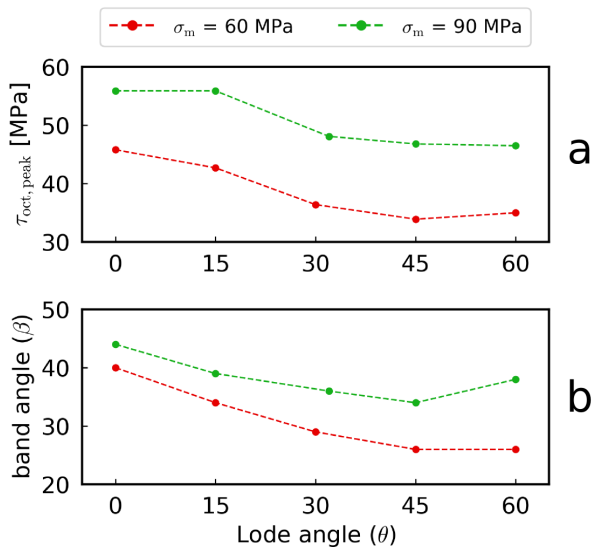


Figure 3. Evolution of the peak stress (a), and the band angle (b) with the Lode angle at the 2 mean stresses of 60 and 90 MPa.

A change in the mechanical response is also observed for experiments at the same mean stress level: in both series of 5 tests, we observe a decrease in the peak stress with increasing Lode angle. This variation is however non-linear as most of the transition appears to be occurring at lower Lode angles (from 0 to 30°); for Lode angles of 30° , 45° and 60° , the peak strength is almost constant. In figure 2a we observe that the transition appears to be more progressive at 60 MPa and abrupt at 90 MPa. The standard deviation of the peak stress decreases at the higher mean stresses (from 5.2 and 4.8 MPa at 60 and 90 MPa respectively), indicating a reduction in the disparity of mechanical properties with increasing mean stress.

At a mean stress of 90 MPa, this change in regime is emphasized by two other global observations: the pre-peak hardening phase for tests σ_m of 90 MPa and θ of 0° and 15° are comparable and significantly different from the trend observed at higher Lode angles (figure 2a); in these two tests the volumetric strain evolution is also distinct from other tests (figure 2b), where a more progressively compactancy and no global sign of dilatancy during the hardening phase is observed.

Full field measurements of strain in the 1-3 plane enabled the identification of localization and its evolution. We use this measurement to characterize the predominant band angle during the transition from a hardening into a softening regime or uncontrolled fracturing. Figure 4 shows a map of the square norm of the 2 dimensional deviatoric strain tensor $\hat{U}-I$, where U is the right stretch tensor, " \wedge " denotes the deviatoric part and I is the identity matrix. This field derived from the displacement field obtained by 2D digital image correlation, is a good indicator of the concentration of the shear deformation.

The observed band angle (β), as it is fully developed across the sample, is known to vary with the degree of ductility in the mode of deformation experienced by the specimen. It is here defined as the angle between the most compressive principal stress (σ_1) and the plane of maximum shear deformation. Figure 3b shows its evolution with the mean stress and the Lode angle. We observe a decrease of the band angle with increasing Lode angle and an increase with the mean stress. This trend is related to observations in peak stress variation.

At a Lode angle of 15° and mean stress of 90 MPa, although the mechanical response of the test is comparable to the test at a Lode angle of 0° , the recorded damage patterns is not as diffuse and is more consistent with ones observed in tests at higher Lode angle, where large deformation occurs in a single shear band.

4 Discussion and Conclusion

The results from this series of stress controlled experiments presents possible effect of various stress paths, expressed by different Lode angles, on the brittle to ductile transition for isotropic porous rocks. This suggests that, in addition to the mean stress level (σ_m), the mode of deformation induced by the distribution of stress in the intermediate and minor principal direction has significant and non-linear repercussions on strength and failure mode.

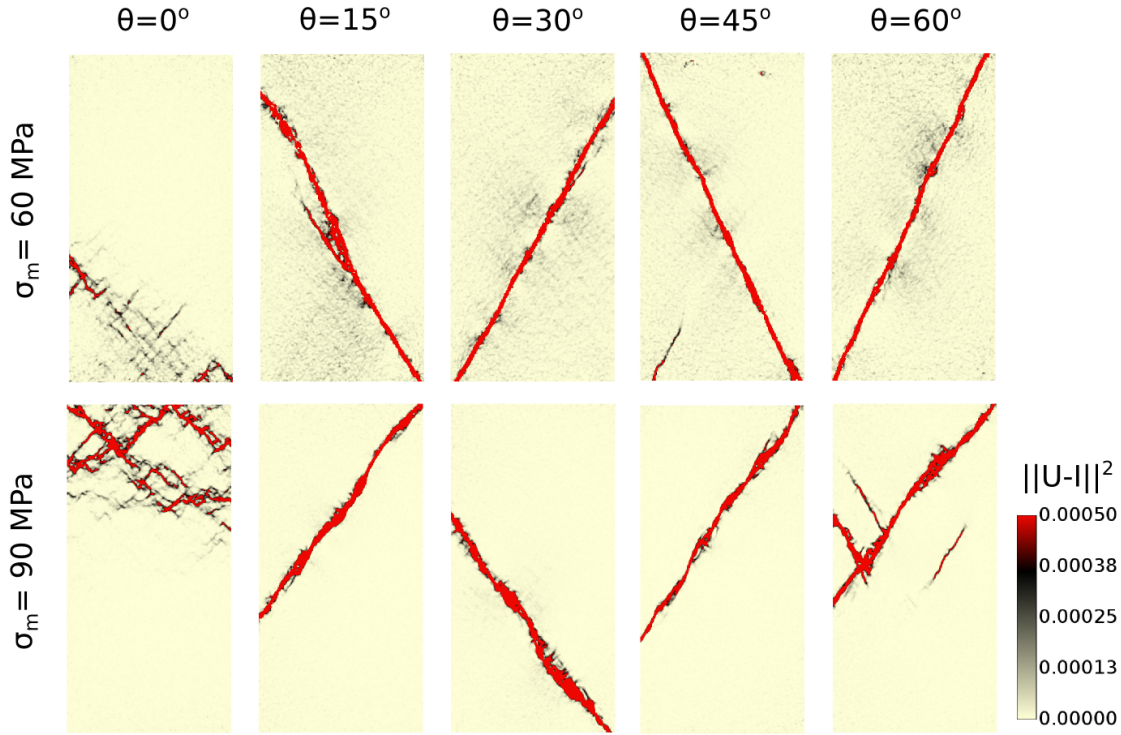


Figure 4. Map of local deviatoric strain around the maximum stress for the 10 samples tests during this experimental campaign.

For failure criteria taking into account variations of strength with Lode angle, the transition in the peak stress will have an impact on the curvature of the failure surface, since, for the stress range studied, resulting from the transition between a brittle to ductile regime. A generic failure surface can be fitted by data points in each deviatoric plane using the Van-Eekelen formula [15] :

$$\tau_{oct}(\theta) = (1 - \alpha \sin(3\theta))^n \quad (2)$$

where n is imposed at -0.229 to preserve convexity of the failure surface and α , an indicator of the degree of curvature, is optimized using a least-square minimization method over the 5 data points at each σ_m .

To conclude, polyaxial experiments coupled with full field 2D measurement techniques proved to enrich our understanding of failure in high porosity sandstone. Experimental measurements done in the scope of this research provide a reference to evaluate and expand bifurcation theory as a way to predict failure and failure mode in rocks.

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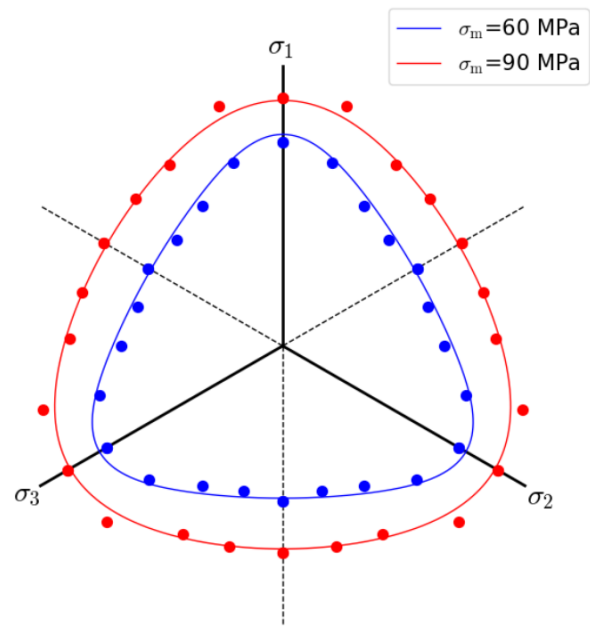


Figure 5. not the exact plot! Van-Eekelen failure surface in the deviatoric plane. The hexagonal sections reflects the symmetries for isotropic material with commutable principal stress directions

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