MEASUREMENT OF DAMAGE LOCALISATION IN ROCKS USING ULTRASONIC VELOCITY MEASUREMENTS/TOMOGRAPHY

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Summary In this paper we present two examples of the use of ultrasonic measurements for the assessment of damage localisation in rocks deformed under laboratory conditions: (1) using multiple point-to-point velocity measurements during a loading experiment on a soft rock with simultaneous full-field strain measurement, which permits a link to be made between velocity changes and deformation; (2) using ultrasonic tomography to obtain full-field measures of velocity in specimens of a Vosges sandstone with localised shear-band features, in which the strain localisation is found to be coincident with localised damage (velocity reduction).

INTRODUCTION

An understanding of strain and damage localisation in rocks is important in many aspects of engineering, including prediction of the distribution and evolution of fluid flow properties in subsurface reservoirs and the mitigation of risks of failure of boreholes. Strain localisation in rocks, at the laboratory scale, can take different forms, from dilatant shear bands to compaction bands and is associated with damage localisation, i.e., the degradation of elastic properties, which can occur through a number of mechanisms. The study of such localisation phenomena requires measurements of fields of variables or properties as opposed to restricted point-wise boundary measures, which cannot capture the heterogeneity resulting from these processes. In recent years a number of developments have been made in experimental mechanics that permit such "full-field measurements". For example, photography and digital image correlation (DIC) allow assessment of displacement and strain fields at the surface of test specimens during loading. This technique has been gaining in popularity in solid mechanics, such that it is now becoming quite common-place, and has, more recently, been employed in laboratory rock-/geo-mechanics (e.g., [1]). Characterisation of damage fields and their evolution is less common, but has been achieved by inverse analyses of DIC strain fields (e.g., [2]) based on predefined damage models. An alternative to inverting damage from DIC is to determine damage distributions using ultrasonic waves that can be considered as propagating according to the elastic properties, and density, of the medium. This can be exploited to provide measures of the medium's (evolving) elastic properties. In particular, ultrasonic tomography, which is quite well developed in the fields of medical and seismic imaging, could provide a full-field technique for damage mapping that compliments DIC measurements. In this paper we present two examples of the use of ultrasonic measurements for the assessment of damage localisation in rocks deformed under laboratory conditions.

METHODS AND RESULTS

In the first example multiple point-to-point velocity measurements were made during a loading experiment on a high-porosity, soft rock (Neapolitan Yellow Tuff - NYT) with simultaneous DIC measurement, which permits a link to be made between velocity changes and deformation (this work was carried out in the context of the PhD thesis of Nguyen, 2011[1]). Parallelpidedic samples of NYT cut to a geometry with two large notches that encouraged the localisation of shear strain the centre of the sample (see Figure 1) were loaded under uniaxial compression (experiments were carried out at GFZ Potsdam). During the loading ultrasonic P-wave measurements were made between a number of transducers attached to the sample surface (see Figure 1). Concurrent acoustic emission and 2D-DIC measurements were also made. The velocity measurements along the different paths are presented in Figure 1 and it can be seen that they all show reducing velocities with increasing time (and thus strain). After about 250 seconds the measured velocities split into two groups, those that pass through the zone of strain localization (as indicated by the DIC plots to the bottom of the Figure) and those that do not. This highlights the association of damage localization with strain localization. Work is on-going to integrate the strain and velocity measurements to better interpret the damage evolution.

In a second example, 2D ultrasonic tomography (involving an inversion of ultrasonic measurements over many directions) has been employed to obtain full-field measures of velocity in cylindrical specimens of a Vosges sandstone

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deformed under triaxial conditions, which resulted in the evolution of localised shear-bands (this work was carried out in the context of the PhD thesis of Charalampidou, 2011[3]). Small notches were made in the sample surface to focus the localization to the centre of the specimens and thus aid the analysis, but samples without notches presented similar deformation behaviour. In this case, the evolution was not followed during testing, but three sister samples taken to different levels of axial strain (and thus of shear-band development) were studied, which provides some indications of the evolution. Measurements for ultrasonic tomography were made (at ISTerre, Grenoble), after the triaxial testing and subsequent unloading of the samples, using two arrays of 64 transducers either side of the specimens at two positions.

Figure 2 presents results of the ultrasonic tomography plus the loading curves and representative vertical slices extracted from x-ray tomography images of the same samples. In each case localised bands of low ultrasonic (P-wave) velocity can be seen in the ultrasonic images, which coincide in position with the zones of increased density in the x-ray tomography images (the localised shear bands). This indicates that the rock has undergone compaction (increased density through porosity reduction), but with associated damage leading to the reduced velocities. Comparison of the results from the three samples indicates the intensification of the damage, and its localisation, with increasing strain after the loading peak. It is also noted that the low velocity zone is significantly larger than the localised zone in the tomography images, this may be due to the lower resolution of the ultrasonic method (dictated by the wavelength, which is restricted itself by the internal length scale of the rock to about 3 mm), but also possibly indicates the occurrence of damage and its detection even with very minor density changes; this is also evident in the VLR0 result where little evidence of localised deformation can be seen in the x-ray image but clear low-velocity anomalies appear in the ultrasonic image. Work is on-going to improve the resolution and accuracy of the ultrasonic tomography to help resolve such issues.

CONCLUSIONS

Ultrasonic velocity measurements provide a good tool to assess damage evolution in rocks. When used in a full-field sense (i.e., through tomography) or in conjunction with other full-field measurements (in this case DIC-strain measurements), new insight can be gained into the damage localisation phenomena associated with strain localisation, as has been demonstrated here in two examples. On-going work includes improvements to the resolution and accuracy of the methods, linking velocity and DIC measurements and performing ultrasonic tomography during loading (with concurrent DIC)[4].

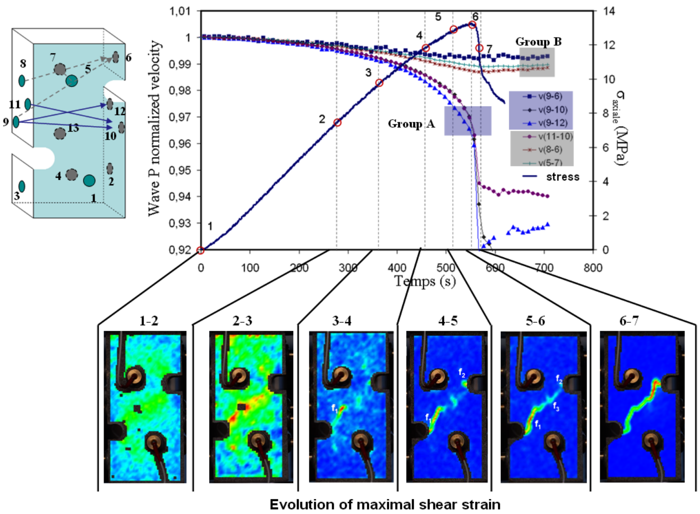

Figure 1: Results from the experiments on NYT including loading curves and velocities along different directions (as indicated in the top-left image) as a function of time. The lower images provide the DIC-derived shear-strain fields for different loading intervals

References

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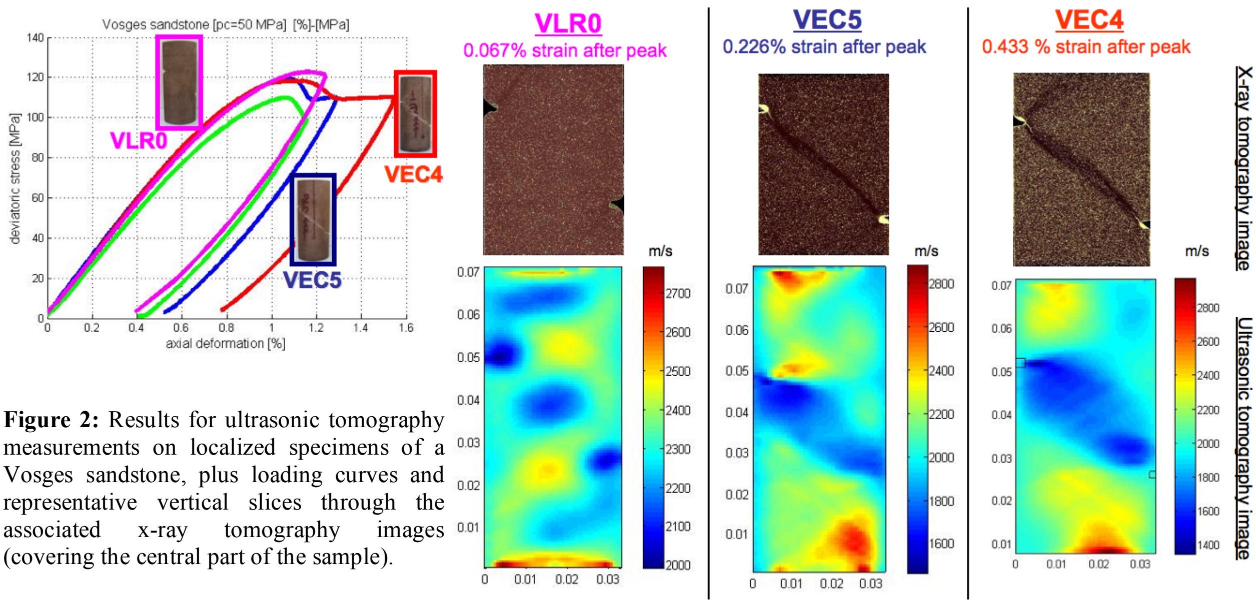

Figure 2: Results for ultrasonic tomography measurements on localized specimens of a Vosges sandstone, plus loading curves and representative vertical slices through the associated x-ray tomography images (covering the central part of the sample).