Journal of Rock Mechanics and Geotechnical Engineering 7 (2015) 136–146

Contents lists available at ScienceDirect

Journal of Rock Mechanics and Geotechnical Engineering

journal homepage: www.rockgeotech.org

Full length article

Full-field mapping of internal strain distribution in red sandstone specimen under compression using digital volumetric speckle photography and X-ray computed tomography

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ARTICLE INFO

Article history:
Received 20 November 2014
Received in revised form
26 January 2015
Accepted 28 January 2015
Available online 4 March 2015

Keywords:
Red sandstone
Strain localization
Uniaxial compression
Digital volumetric speckle photography (DVSP)
X-ray micro-tomography

ABSTRACT

It is always desirable to know the interior deformation pattern when a rock is subjected to mechanical load. Few experimental techniques exist that can represent full-field three-dimensional (3D) strain distribution inside a rock specimen. And yet it is crucial that this information is available for fully understanding the failure mechanism of rocks or other geomaterials. In this study, by using the newly developed digital volumetric speckle photography (DVSP) technique in conjunction with X-ray computed tomography (CT) and taking advantage of natural 3D speckles formed inside the rock due to material impurities and voids, we can probe the interior of a rock to map its deformation pattern under load and shed light on its failure mechanism. We apply this technique to the analysis of a red sandstone specimen under increasing uniaxial compressive load applied incrementally. The full-field 3D displacement fields are obtained in the specimen as a function of the load, from which both the volumetric and the deviatoric strain fields are calculated. Strain localization zones which lead to the eventual failure of the rock are identified. The results indicate that both shear and tension are contributing factors to the failure mechanism.

1. Introduction

The macroscopic deformation and failure of rock is a gradual process of damage accumulation, crack initiation, propagation, interaction and then the eventual failure (Amitrano, 2006). Failure first manifests itself with the appearance of strain localization and then the creation of a damage zone. The localization of damage and strain will result in the stress redistribution and thus weaken the mechanical performance of the rock. In order to understand the mechanisms and evolution of damage or strain localization in rocks, full-field deformation measurement methods, such as stereophotogrammetry (Desrues and Viggiani, 2004) and digital image correlation (DIC) (Kozicki and Tejchman, 2007; Hall et al., 2010a, b; Dautriat et al., 2011; Nguyen et al., 2011; Lin and Labuz, 2013; Zhang et al., 2013) have been used, mostly with two-dimensional (2D) images obtained from plane strain experiments. But the 2D observations are limited in their capability to resolve the geometric complexities and heterogeneity in geomaterials.

X-ray computed tomography (CT), as a non-destructive three-dimensional (3D) imaging technique, has been used to investigate the internal structures, deformation localization and failure of geomaterials. In applications of the X-ray CT, the loading test and the scanning were not conducted simultaneously (Desrues et al., 1996; Alshibli et al., 2000). Only the density of the specimen or the CT number distribution inside the specimen was used to reveal the localized zones (Bésuelle et al., 2000; Viggiani et al., 2004; Louis et al., 2006; Suzanne et al., 2008). The 2D DIC technique has been employed to analyze radiography (Louis et al., 2007) or the sectional CT images (Adam et al., 2008) for assessing the internal deformation patterns in the geomaterials. A significant limitation of this approach is the fact that it only allows the quantification of 2D displacement field and 2D strain distribution in the sectional plane while ignoring the out-of-plane displacement all together (Adam et al., 2013). This information is not sufficient to fully evaluate the onset and evolution of localized deformation. Bay et al. (1999) developed a 3D strain mapping technique using 3D digital image volume correlation, called digital volume correlation (DVC), and have measured displacement and strain fields in trabecular bones

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Peer review under responsibility of Institute of Rock and Soil Mechanics, Chinese Academy of Sciences.

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http://dx.doi.org/10.1016/j.jrmge.2015.01.003

under compression. By combining in situ CT scanning and DVC, some studies have been carried out on a number of geomaterials, such as rocks (Lenoir et al., 2007; Charalampidou et al., 2011, 2014) and granular materials (Hall et al., 2010a, b; Adam et al., 2013). In the DVC method, a cubic subset surrounding the interrogated point located in the reference volume image is selected and correlated with the corresponding location in the deformed volume image. The resulting displacement vector is obtained. The theory is simple. But in the practical implementation due to the vastly increased volume of data associated with the undeformed and deformed images and the increased degree-of-freedom (DOF), the DVC is facing some challenges, such as the implementation complexity, the measurement accuracy and the computational efficiency (Pan et al., 2012). Digital volumetric speckle photography (DVSP) is another 3D strain analysis technique, which is the extension of 2D digital speckle photography (DSP) technique that offers some advantages over the DVC technique in the computational efficiency. Details of the evolution of the speckle technique leading to the development of DVSP can be found in Chiang and Mao (2015).

In this study, we apply the DVSP technique in conjunction with X-ray micro-tomography to obtain the 3D interior strain fields in a red sandstone specimen under uniaxial compression, and then discuss the accuracy of DVSP technique.

2. Experimental procedure

2.1. Experimental setup and imaging procedure

In this study, the main components of the industrial X-ray CT system are a microfocus X-ray source from YXLON (FeinFocus 225 kV), a X-ray detector unit (1024 pixel × 1024 pixel) from PerkinElmer (XRD 0822AP 14), and a motorized rotation stage from Newport, USA. The X-ray has a focus with size of 3 μm × 6 μm, a voltage range of 50–225 kV, and the tube current ranging from 0 to 1440 μA. A simple uniaxial compression setup is designed and built that would allow the operation of micro-tomography of a specimen under load in situ. The setup cell is made of PMMA, which is transparent to X-rays. The CT system and loading setup are shown in Fig. 1.

A cylindrical specimen of red sandstone of ϕ25 mm × 50 mm in size and a porosity of 23.3% is placed in the cell. The compaction of the specimen is achieved by applying a compressive load in the axial (z) direction. The X-ray source to the specimen and source-to-detector distances are 139 mm and 696 mm, respectively, resulting in a 5.0 times magnification. The whole compression process is divided into 8 steps. In each step, the loading is kept constant while the specimen is scanned. During the scanning, 720 projections are captured and distributed at equal angles over 360°. It takes 25 min to scan the specimen in each loading step. After scanning, the reconstruction is carried out with the Feldkamp cone-beam reconstruction algorithm. The reconstructed volume images have 566 voxel × 566 voxel × 954 voxel (where a "voxel" is the 3D equivalent of a pixel) and cover the specimen with height of 43 mm. The physical size of a voxel is 45 μm^3. Based on the projection image of the specimen in each loading step, the global displacement along z-axis is measured, from which the axial strain is obtained. The stress–strain curve from the loading history is shown in Fig. 2. Because the metal compression disks influence the top and bottom slice images, only the middle of the volume image with size of 566 voxel × 566 voxel × 801 voxel is analyzed. In Fig. 3, the reconstructed volume image of step 8, three orthogonal sections, and sectional images along $x = 12.5$ mm and $y = 12.5$ mm of steps 7 and 8 are shown, respectively.

Fig. 4 shows the gray value distribution curves throughout the volumetric images at different loading steps. It is noted among these curves that the distributions for steps 6 and 7 are slightly narrower than those of other steps. Table 1 lists the mean gray values and the standard deviations. It can be seen that the mean gray value has a slightly higher increment from step 1 to step 4, indicating globally a lower porosity and higher density; and then declines after step 4, indicating a higher porosity and lower density. This implies that the initial microcracks are closed under compressive loading before step 4, and microcrack development makes the specimen dilatant after step 4. However, gray value distribution curves and CT gray level images alone are not very effective in differentiating the strain localization area nor the microcrack onset and development. Thus, to shed more light on the deformation characteristics of the specimen, the newly developed full-field strain measurement technique, DVSP, is employed as follows.

2.2. Elements of the DVSP technique

From the sectional images shown in Fig. 3, it can be seen that there are several components and pores in the red sandstone, and different components have different gray values. This natural structure can be regarded as a pattern of volumetric speckles pattern and carries the information of deformation. This naturally presented structural pattern is used in the analysis adopting the DVSP technique. The volumetric image of step 1 is defined as the reference volumetric image, and the volumetric image of step 2 is defined as the deformed one. They are then divided into subsets with a cubic array of 64 voxel × 64 voxel × 64 voxel; there is a 32-voxel overlap between neighboring subsets, and then compared.

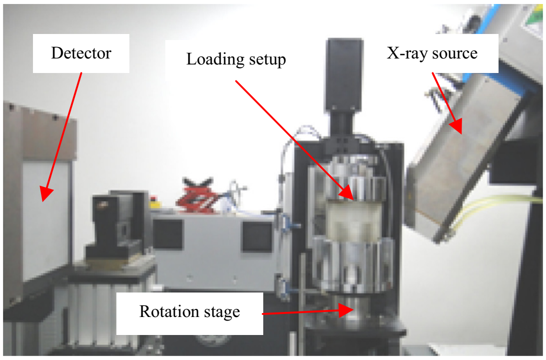

Fig. 1. Industrial CT and loading setup.

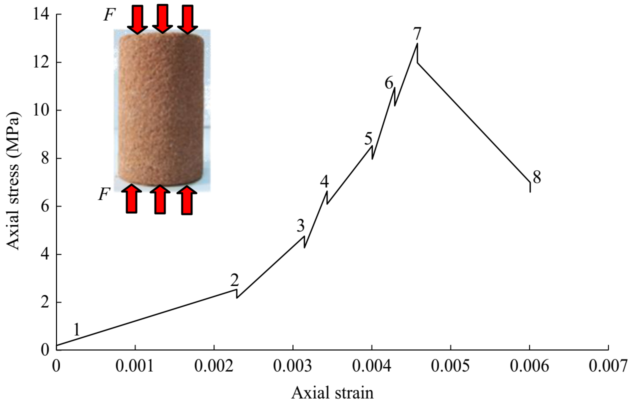

Fig. 2. Stress-strain curve.