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Quantitative 3D strain analysis in analogue experiments simulating tectonic deformation: Integration of X-ray computed tomography and digital volume correlation techniques

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ABSTRACT

The combination of scaled analogue experiments, material mechanics, X-ray computed tomography (XRCT) and Digital Volume Correlation techniques (DVC) is a powerful new tool not only to examine the 3 dimensional structure and kinematic evolution of complex deformation structures in scaled analogue experiments, but also to fully quantify their spatial strain distribution and complete strain history.

Digital image correlation (DIC) is an important advance in quantitative physical modelling and helps to understand non-linear deformation processes. Optical non-intrusive (DIC) techniques enable the quantification of localised and distributed deformation in analogue experiments based either on images taken through transparent sidewalls (2D DIC) or on surface views (3D DIC). X-ray computed tomography (XRCT) analysis permits the non-destructive visualisation of the internal structure and kinematic evolution of scaled analogue experiments simulating tectonic evolution of complex geological structures. The combination of XRCT sectional image data of analogue experiments with 2D DIC only allows quantification of 2D displacement and strain components in section direction. This completely omits the potential of CT experiments for full 3D strain analysis of complex, non-cylindrical deformation structures.

In this study, we apply digital volume correlation (DVC) techniques on XRCT scan data of "solid" analogue experiments to fully quantify the internal displacement and strain in 3 dimensions over time. Our first results indicate that the application of DVC techniques on XRCT volume data can successfully be used to quantify the 3D spatial and temporal strain patterns inside analogue experiments. We demonstrate the potential of combining DVC techniques and XRCT volume imaging for 3D strain analysis of a contractional experiment simulating the development of a non-cylindrical pop-up structure. Furthermore, we discuss various options for optimisation of granular materials, pattern generation, and data acquisition for increased resolution and accuracy of the strain results.

Three-dimensional strain analysis of analogue models is of particular interest for geological and seismic interpretations of complex, non-cylindrical geological structures. The volume strain data enable the analysis of the large-scale and small-scale strain history of geological structures.

1. Introduction

Analogue models have been used since the early 19th century to investigate the evolution of deformation structures in the Earth's crust and lithosphere (Hall, 1815; Daubre, 1879; Cadell, 1887). Traditionally, structural evolution was observed at the model's surface, through transparent sidewalls or by cutting sections through the model at the end of the experiment. Major advances in the scaling theory during the 20th century (Hubbert, 1937; Ramberg, 1967) have expanded analogue experiments from a qualitative technique and conceptual modelling tool to a quantitative technique (Koyi, 1997; Costa and Vendeville, 2002) relating the comparison of model geometry, kinematics and stresses to their natural prototypes.

In recent decades, new full-field imaging techniques and full-field strain monitoring methods have been introduced which

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allow a more complete analysis of the spatial and temporal evolution of structures in scaled analogue experiments on all appropriate scales. Since the late 1980s, non-destructive X-ray computed tomography (XRCT; Hounsfield, 1972) has been applied to visualize the internal structure and kinematic evolution of analogue models (Mandl, 1988; Colletta et al., 1991). This technique permits the non-destructive visualisation of the internal structure and kinematic evolution of scaled analogue experiments. Technological improvements have resulted in more powerful XRCT scanners with higher image resolution and faster image acquisition.

The higher image resolution of X-ray micro-tomography scanners (μXRCT) enables the detailed imaging of particles and pore space in granular material samples. Recent applications of μXRCT in granular material analysis demonstrate its capability to obtain detailed information about shear band geometries and shear deformation (Hall et al., 2010a; Pannier et al., 2010; Ando et al., 2012). Faster image acquisition of large XRCT scanners for material testing and medical purposes allows repeated acquisition of large volumetric data sets, thus making it possible to follow the 3D evolution of the deformation structures in analogue experiments (e.g. Schreurs et al., 2002, 2003).

The application of modern digital image correlation (DIC) methods enables the full-field measurement of displacement fields and related strains in geomaterial tests (Viggiani and Hall, 2008) and analogue experiments (Adam et al., 2005). DIC is a mathematical tool for assessing the spatial transformation, e.g. translation and distortion of image data (Sutton et al., 1986; White et al., 2003). 2D DIC of images, 3D DIC of stereo image pairs and 3D volumetric DIC (DVC) of tomographic or seismic volume data are applied for deformation and flow analysis in material mechanics, analogue experiments, fluid mechanics (Particle Imaging Velocimetry – PIV), medical imagery and 4D seismic analysis of hydrocarbon reservoirs under production (Hall, 2006).

In the last decade, DIC and DVC methods have been widely applied in material sciences and geomechanics (McDonald et al., 2006; Pierron et al., 2011) ranging from 2D deformation analysis (Wolf et al., 2003; Hall et al., 2010b) to 3D deformation analysis of granular materials (Ando et al., 2012). The development of discrete particle tracking and discrete 3D DIC techniques enables the analysis of 3D particle kinematics in μXRCT images of granular materials (Hall et al., 2010a, 2012; Smit, 2010; Ando et al., 2012).

The application of optical 2D and 3D DIC techniques represented an important advance in the quantitative analysis of deformation processes in analogue experiments (Adam et al., 2005). Since their introduction, DIC measurement techniques have enjoyed broad acceptance in the community of tectonic modellers with applications in various disciplines ranging from 2D strain analysis in fracture analysis (Nguyen et al., 2011), fault mechanics (van Gent et al., 2010), shear zone evolution in natural rock materials (Louis et al., 2007; Schrank et al., 2008; Charalampidou et al., 2010; Dautriat et al., 2010) and from tectonic simulations of convergent plate margins (Hoth et al., 2006; Rosenau et al., 2008; Yamada et al., 2009) to 3D stereo DIC analysis of the evolution and deformation of complex model surfaces in experiments simulating tectonic material transfer at convergent margins (Hampel et al., 2004) and gravity-driven deformation at passive margins (Krezsek et al., 2007; Adam et al., 2012; Adam and Krezsek, 2012).

Optical DIC provides an accurate measure of the incremental 2D/3D displacement field in analogue experiments and enables the complete quantification of localized and distributed deformation of the exterior of an analogue model at a high spatial and temporal resolution (Adam et al., 2005). In the analogue experiments, 2D DIC strain analysis is applied to time-series sectional images taken through transparent sidewalls, whereas 3D stereo DIC deformational analysis requires time-series stereoscopic image sets of model surfaces. Optical DIC enables spatial resolutions of the displacement vectors in the range of the particle size of the granular material (Sutton et al., 1986; White et al., 2003). Due to the computational analysis the temporal resolution (i.e., deformation velocity or displacement rate) is only limited by the recording rate of the imaging system.

A disadvantage of applying optical 2D DIC to images taken through transparent sidewalls is that lateral sidewall friction influences the geometry of the analogue model and that the geometry of the structure visible through the sidewall is potentially distorted and not necessarily representative for the internal structures as imaged by XRCT methods. 2D DIC techniques have also been tested on sequential XRCT data, representing successive sections through the interior of an initially horizontally layered analogue model that was shortened above a basal detachment (Adam et al., 2008). Although the internal deformation was monitored successfully by 2D DIC, the layered nature of the model limited the resolution of the strain results. Horizontal layers and elliptical to disk-shaped material variations cause problems for accurate displacement vector correlation in the direction parallel to material contrasts, which limits the spatial resolution of the vector field as well as the accurate presentation of minor strain variations and displacement discontinuities (Adam et al., 2008). A significant limitation of 2D DIC techniques applied to sectional XRCT images of analogue experiments is that it only allows quantification of 2D displacement and 2D strain components in section direction, ignoring out-of-section movement of material. Consequently, 2D DIC is not capable of providing an accurate strain representation for complex, non-cylindrical deformation structures.

In contrast to 2D/3D DIC analysis, digital volume correlation (DVC) is based on digital cross correlation of intensity values or particle patterns in time-series volumetric data. DVC of XRCT data enables a truly 3D deformation analysis and has already been successfully applied in material sciences and geomaterial testing. In this study we explore the potential of applying DVC techniques to XRCT volumetric data sets in order to quantify the temporal and spatial 3D material transfer and strain history of large analogue experiments. These experiments are characterized by model volumes that are typically 2–3 orders of magnitude larger than samples used in material tests.

To test the applicability of DVC to XRCT data of large analogue experiments, we performed two 3D experiments simulating the evolution and kinematics of transfer zones in fold-and-thrust belts

Table 1
Summary of experiments conducted for digital imaging correlation (DIC) and digital volume correlation (DVC); keV: kilo-electron voltage; mA s: milli-ampere-second.

Experiment (EXP)	Granular materials	Maximum shortening	Number of volume scans per deformation step	Type of CT scanner	Applied energies	Scan procedure slice thickness	Size of EXP: width, length thickness	Current results
360	UBESAN sand, ceramic spheres	7 mm	5	Siemens Sensation 64	120 keV; 200 mA s	2 mm	20 cm, 30 cm, 3 cm	3D DVC cross-sections
385	GFZSAN sand, ceramic spheres	15 mm	2	Siemens Emotion 6	130 keV; 200 mA s	2.5 mm	20 cm, 30 cm, 3 cm	Image processing test