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Review

Quantitative characterization of deformation and damage process by digital volume correlation: A review

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HIGHLIGHTS

- This paper detailedly reviewed the applications of DVC in quantitative characterization of material deformation, damage, and crack propagation. It would help the researchers to understand the current research status of DVC.
- Furthermore, this paper discussed the current research focus of DVC and stated that efficient algorithms and high-resolution 3D experimental methods should be important research direction in future. This paper is hopeful to provide guidance on the development of DVC.

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ABSTRACT

Characterizing material 3D deformation and damage is a key challenge in mechanical research. Digital volume correlation (DVC), as a tool for quantifying the internal mechanical response, can comprehensively study the extraction of key failure parameters. This review summarizes the recent progresses in the study of the internal movement of granular materials, inhomogeneous deformation of composite materials, and stress intensity factor around a crack front in static and fatigue states using DVC. To elaborate on the technique's potential, we discussed the accuracy and efficiency of the algorithm and the acquisition of real microstructure data within the material under a complex environment.

1 Introduction

Digital volume correlation (DVC) technology combined with internal imaging methods, such as X-ray microcomputer tomography (XCT) [1], confocal microscopy (CM) [2], and magnetic resonance imaging (MRI) [3], can be used for many comprehensive in situ investigations on bones [4], cells, soft gels, granular materials, foams, ceramics, polymers, and metals and their alloys. The technology can effectively quantify the mechanical responses of internal microstructures. Through the in-depth study of the mechanism of material deformation and damage, many problems (such as the representing strain inhomogeneity and extracting the crack-tip stress intensity factor (SIF)) must be solved from a higher dimension and a special structure within the material, rather than simplifying into a plane problem. In certain materials (such as ceramics, rocks, and concrete), destruction is a sudden process; the internal deformation process of such materials is difficult to study intuitively only through the structural changes. By contrast, DVC, a quantitative representation of the tool, holds great potential in characterizing internal deformation damage and extracting related parameters.

In 1999, Bay et al. [1] proposed a digital correlation method for measuring the 3D displacement field and strain field of uniaxial compression bone for the first time. The DVC method fundamentally enhanced the level of evolutionary information obtained in 3D imaging and would hence potentially benefit the field of biomaterials. The general calculation format of DVC comprises two stages (Fig. 1) [5-9]. The first stage is the 3D displacement field calculation, which means specifying the interrogated points within the volume image before deformation and

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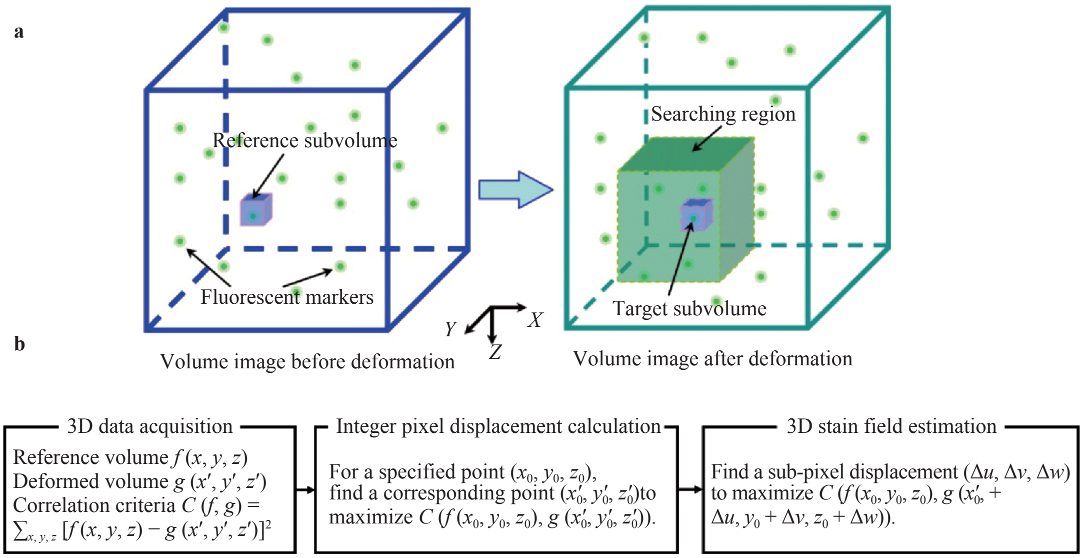

Fig. 1. **a** General format of digital volume correlation calculation [9]. **b** Schematic diagram of the overall process of DVC

tracking their corresponding locations in the volume image after deformation to extract their 3D displacement vectors caused by exerted loading. The second stage is the 3D strain field estimation, which means calculating the strain components from the discrete displacement vector field using an appropriate correlation criteria and shape functions. In recent years, the combination of high-precision and high-efficiency DVC with high-resolution computed tomography technology has greatly expanded breadth and depth of the research scope of DVC applications in 3D problems. In this review, we introduced the applications of DVC in numerous fields, such as the cell migration, internal movement of granular materials, the discharge process of electrode materials, deformation of porous materials and composites, crack initiation and fracture of brittle materials, extraction of the SIF of crack fronts, and the fatigue crack closure effect.

Furthermore, the current research focus of DVC, which should be more accurate and more efficient, was discussed. Optimizing DVC algorithms should be the main approach to improve computing efficiency until computing hardware are developed sufficiently in the future. Besides, novel experimental methods which can acquire high-resolution internal 3D information would greatly influence the accuracy of DVC. Combining efficient algorithms and high-resolution 3D information, the application of DVC method would be greatly extended and might bring internal mechanical behavior study into a new stage.

2 Applying DVC in studying deformation and damage process

3D images obtained from previous experiments are often consulted for visual judgments. However, these judgments based on visual images cannot directly contribute to quantitative analysis. The DVC method can obtain image sequence of the structural evolution between the material's responses to the deformation under the load. The DVC method can measure the internal deformation of the load object and provide a powerful means to study the internal strain and failure process of the composite specimen. Many scientific problems in mechanics also possess quantitative and meticulous characteristics. Solving these components require accurate theoretical description and quantitative calculations, which can be satisfied by DVC's ability to achieve quantitative structural deformation parameters. In recent years, DVC has been widely used for mechanical research in numerous fields. Characterizing movement, strain field evolution, and behavior in the crack-tip zone by DVC method is reviewed in the following sections.

2.1 Tracing of target object movement

The classical continuum theories (which do not consider internal length parameters) are limited and instruments that can visualize particle movements at the microscopic level are lacking. Furthermore, the available computational tools for quantitative measurements are insufficient. Given these shortcomings, only a few studies have been developed to describe the internal structure of materials. Along with high-resolution 3D XCT, DVC can recognize the granular material in the external shear, biological growth, and other external actions under particle movement. As such, DVC helps illuminate the orientation and law of grain movement. Moreover, DVC can be used to intensively study bio-active cells and tissue through cell movement and implant micro-movement and hence increase the understanding on cell migration and joint repair. DVC can also quantify the local displacement of electrode materials during the charge–discharge process of energy materials (such as lithium ion battery). The resultant information helps increase understanding on the mechanism of micro-scale structure evolution. Therefore, this section reviews the application of DVC in tracing target object movement from three aspects: the movement of grain, the movement of cell and implant, and local displacement of electrode materials.

When a large soil amount is sheared, the deformation is usually positioned as a strong shear region called a shear band. To describe the internal structure of the shear band, A. Hasan et al. proposed a quantitative assessment of the spatial changes of particle orientation, contact, and porosity in sand samples loaded under plane strain conditions [10]. This measurement can be used to validate the model of the deformation behavior