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Morphological evolution and internal strain mapping of pomelo peel using X-ray computed tomography and digital volume correlation

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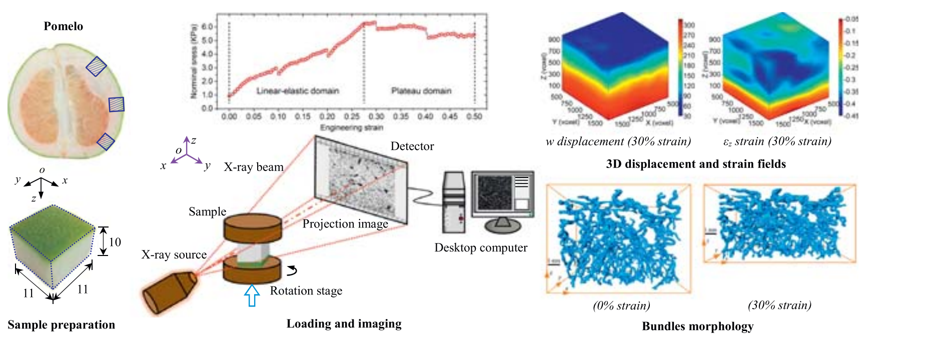
HIGHLIGHTS

- Compression tests of pomelo peels were performed with in-situ microstructure visualization and full-field strain mapping.
- X-ray CT imaging and DVC were used to quantify its morphological evolution and deformation responses.
- Non-uniform through-thickness microstructure composition and deformation distributions were observed.
- Linear correlation is found between compressive strains and the variations of two key morphological features.

GRAPHICAL ABSTRACT



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ABSTRACT

Cellular microstructures within natural materials enlighten and promote the development of novel materials and structures in the industrial and engineering fields. Characterization of the microstructures and mechanical properties of these natural materials can help to understand the morphology-related mechanical properties and guide the structural optimization in industrial design. Among these natural cellular materials, pomelo peels, having a foam-like hierarchical microstructure, represent an ideal model for developing materials with high energy absorption efficiency. In this work, by combining X-ray tomographic imaging technique and digital volume correlation (DVC), in-situ stepwise uniaxial compression tests were performed to quantify the internal morphological evolution and kinematic responses of pomelo peel samples during compression. Via these experiments, the varying microstructure features and thus diverse resistance to compression from endocarp to exocarp are examined, and the evolution of both bundles bending and large strain domain from endocarp to mesocarp are explored. Based on the experimental results, the microstructure-related mechanical properties of pomelo peels in response to compressive loading that demonstrates nearly linear morphology-mechanics relationship were revealed.

1. Introduction

Multi-scale porous micro-architectures in natural materials provide excellent mechanical properties based on limited constituent elements [1–3]. These natural microstructures are enlightening as they provide new perspective for designing and developing new materials with specific mechanical properties by structural optimization rather than by substituting material constituents [4–8]. In the fields of industrial design, both polymer-based and metallic foams have found widespread use nowadays. Realizing desirable mechanical properties by a bio-inspired optimization of the microarchitecture would be a promising method to expand the application of cellular foams. Modified investment casting and 3D printing [9] are well-suited techniques allowing

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for manufacturing these complex or hierarchical structures. With the aid of these techniques, we could fabricate bioinspired cellular materials or components using structures obtained by rapid prototyping as templates for the manufacturing process.

Among numerous natural materials, pomelo peel, a foam-like fiber-reinforced biological tissue, is capable of dissipating considerable kinetic energy when hitting the ground after falling from the tree, thus providing guidance for developing lightweight impact resistant materials via establishing hierarchical structure [10–12]. To understand the biomechanical mechanism of pomelo peel, research efforts have been dedicated to reveal its deformation response [13], mechanical behavior [14] and structure-function relationship [15] in 2D case. However, due to their complex multiple-scale microstructure and non-linear mechanical properties, surface analysis is insufficient to reveal the internal mechanisms of deformation response and microstructure evolution. Accurate in-situ full-field internal strain mapping of pomelo peel in response to external loading, which can help to deeper understand their extraordinary microstructure-related mechanical performance, has not been reported so far.

Taking advantage of more accessible volumetric imaging devices, greatly increased computational power of modern computers and constantly refined imaging processing algorithms, digital volume correlation (DVC) [16–18] has experienced rapid growth in recent years and evolved into a powerful internal strain mapping technique. In combination with X-ray micro-computed tomography (micro-CT) imaging technique that allows to visualize internal micro-architectures of a specimen [19–23], DVC can provide data needed to characterize the mechanical behavior of materials in response to external loadings. Since the first application of DVC for strain mapping in bone tissue, subsequent DVC applications to various hard (e.g. bone, tooth, wood) [18,24,25] and soft (e.g. *cornea*) [26] biological tissues have been extensively reported in recent decade.

By combining high-resolution X-ray micro-CT and DVC technique, 3D microstructure visualization and internal full-field strain mapping of pomelo peel samples under compression were realized in this work, and their morphological evolution in response to various compressive strains was then investigated. To this end, carefully designed stepwise uniaxial compression experiment of pomelo peel samples was conducted, during which a lab X-ray micro-CT system was employed to record the volume images of complete pomelo peel samples in different loading stages. Then, based on these acquired volume images, Avizo software and DVC were employed to determine the corresponding microstructural changes and internal full-field deformations, respectively. In this manner, a quantitative understanding of the internal morphology-deformation relationship and the microstructure-related mechanical properties of pomelo peel under compaction was achieved. Inspired by the experimental results observed in this work, the mechanical properties of foam-based components can be possibly enhanced by mimicking the hierarchical structures in pomelo peel.

2. Digital volume correlation

By comparing two volume images of a test sample acquired at different states captured by a volumetric imaging device, DVC can retrieve full-field internal 3D displacement and strain fields. Generally, DVC technique first defines a series of regularly distributed discrete calculation points within the specified reference volume image. Afterwards, deformed positions of these calculation points are tracked in the deformed volume images to extract the full-field displacement vector as exhibited in Fig. 1. Finally, 3D full-field strain can be estimated by differentiating the 3D displacement fields using proper numerical differentiation approach.

In this work, a flexible and accurate DVC approach, which applies an advanced 3D inverse-compositional Gauss-Newton (IC-GN) algorithm to subvoxel registration [27,28], is used to realize full-field internal displacement measurement. Also, a pointwise least-square (PLS) approach is adopted to extract strain maps from computed displacement fields. For completeness, the displacement tracking algorithm and strain estimation approach are described hereafter.

In using 3D IC-GN algorithm for displacement tracking, a robust zero-mean normalized sum-of-square difference (ZNSSD) criterion combined with a first-order shape function is employed to quantify the similarity between the reference and deformed subvolumes.

$$C_{ZNSSD}(\Delta\mathbf{p}) = \sum_{\boldsymbol{\xi}} \left\{ \frac{[f(\mathbf{x}+\mathbf{W}(\boldsymbol{\xi};\Delta\mathbf{p}))-f_m]}{\sqrt{\sum_{\boldsymbol{\xi}}[f(\mathbf{x}+\mathbf{W}(\boldsymbol{\xi};\Delta\mathbf{p}))-f_m]^2}} - \frac{[g(\mathbf{x}+\mathbf{W}(\boldsymbol{\xi};\mathbf{p}))-g_m]}{\sqrt{\sum_{\boldsymbol{\xi}}[g(\mathbf{x}+\mathbf{W}(\boldsymbol{\xi};\mathbf{p}))-g_m]^2}} \right\}^2 \quad (1)$$

where $f(\mathbf{x})$ and $g(\mathbf{x})$ are the respective gray values at point $\mathbf{x} = (x, y, z)^T$ within reference and deformed subvolumes; f_m and g_m the average grayscales within reference and deformed subvolumes; $\boldsymbol{\xi} = (\Delta x, \Delta y, \Delta z)^T$ is the local coordinates of integer-voxel point in the subvolume; $\mathbf{p}$ the deformation vector of the target subvolume; $\Delta\mathbf{p}$ the incremental deformation vector to be determined; $\mathbf{W}(\boldsymbol{\xi}; \mathbf{p})$ is the warp function used to approximate the underlying deformation of the target subvolume; $\mathbf{W}(\boldsymbol{\xi}; \Delta\mathbf{p})$ the incremental warp function exerted on the reference subvolume. To solve the incremental deformation vector $\Delta\mathbf{p}$, Gauss-Newton algorithm [27,28] is employed to optimize the defined ZNSSD function. Then, the incremental warp $\mathbf{W}(\boldsymbol{\xi}; \Delta\mathbf{p})$ of the reference subvolume can be estimated, which is further inverted and composed with the current estimate $\mathbf{W}(\boldsymbol{\xi}; \mathbf{p})$ to determine the updated warp function of the target subvolume. The iterative calculation of incremental

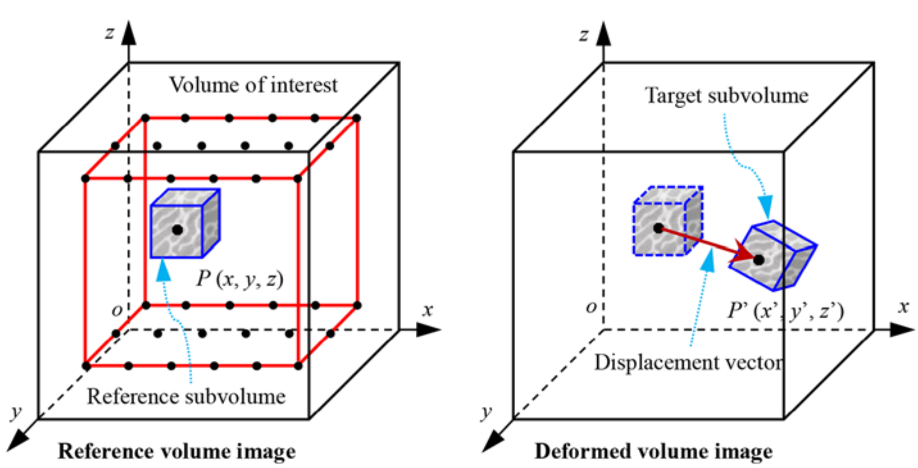

Fig. 1. Basic principle of DVC: matching the same subvolumes located in the reference and the deformed volume images yields the desired 3D displacement vector.