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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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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.

Keywords: Pomelo peel, Digital volume correlation, X-ray tomographic imaging, 3D deformation measurement

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 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 and dissipation. Accurate *in-situ* full-field internal strain mapping of pomelo peel in response to external loading, which can help to deeper understand their extraordinary impact

resistance 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 paper, 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.

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

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.

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

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; $\xi=(\Delta x, \Delta y, \Delta z)^T$ 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; $\mathbf{W}(\xi; \mathbf{p})$ is the warp function used to approximate the underlying deformation of the target subvolume; $\mathbf{W}(\xi; \Delta \mathbf{p})$ the incremental affine 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 $\mathbf{W}(\xi; \Delta \mathbf{p})$ of the reference subvolume can be estimated, which is further inverted and composed with the current estimate $\mathbf{W}(\xi; \mathbf{p})$ to determine the updated warp function of the target subvolume. The iterative calculation of incremental deformation vector $\Delta \mathbf{p}$ is repeated until the preset convergence conditions are reached. Finally, the deformation parameter $\mathbf{p}$ of the target subvolume can be extracted from the final estimate $\mathbf{W}(\xi; \mathbf{p})$.

Due to the influence of various error sources such as noise and image artifacts, DVC-measured displacements generally contain discontinuities or noise, and may be amplified during strain estimation. Therefore, a practical 3D PLS approach [29] is adopted in this work to enhance the strain calculation accuracy by using a simple local fitting scheme. Specifically, to evaluate the strain components of each considered point, a regular cubic domain with a size of $(2N+1) \times (2N+1) \times (2N+1)$ discrete points surrounding the interrogated point is selected first. When the selected strain calculation domain is small enough, the internal displacements along three directions can be reasonably assumed to be linearly distributed. As such, the displacements within the domain is written as

$$\begin{cases} u(x, y, z) = a_1 + a_2 x + a_3 y + a_4 z \\ v(x, y, z) = b_1 + b_2 x + b_3 y + b_4 z \\ w(x, y, z) = c_1 + c_2 x + c_3 y + c_4 z \end{cases} \quad (2)$$

where x, y, z are the local coordinates within the strain calculation box at a range of $-N$ to N , a_i, b_i, c_i ($i=1,2,3,4$) the unknown polynomial coefficients to be determined, u, v, w the DVC-measured full-field displacements in x, y and z directions. After determining the fitted coefficients, the six Cauchy strain components $\varepsilon_x, \varepsilon_y, \varepsilon_z, \gamma_{xy}, \gamma_{xz}$ and γ_{yz} at the interrogated point can be calculated as

$$\begin{cases} \varepsilon_x = \frac{\partial u}{\partial x} = a_2, & \gamma_{yz} = \frac{1}{2} \left(\frac{\partial v}{\partial z} + \frac{\partial w}{\partial y} \right) = \frac{1}{2} (b_4 + c_3) \\ \varepsilon_y = \frac{\partial v}{\partial y} = b_3, & \gamma_{xz} = \frac{1}{2} \left(\frac{\partial u}{\partial z} + \frac{\partial w}{\partial x} \right) = \frac{1}{2} (a_4 + c_2) \\ \varepsilon_z = \frac{\partial w}{\partial z} = c_4, & \gamma_{xy} = \frac{1}{2} \left(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} \right) = \frac{1}{2} (a_3 + b_2) \end{cases} \quad (3)$$

3. Experiments

3.1 Sample preparation and mechanical tests

A honey pomelo (originated in China) was bought at a local market. Its peel was excised from the pomelo fruit to remove remnants of the fruit pulp. As shown in Fig.2, six cubic pomelo peel samples (with a size of $11 \times 11 \times 10 \text{ mm}^3$) located in different region of the pomelo were prepared and trimmed with a cutter knife to get a flat outer surface. The size of these samples was measured with a vernier caliper to ensure the dimensional error less than 0.1 mm.

Fig.2 Prepare process of the test sample: (a) the whole pomelo, (b) longitudinal section of the pomelo (c) one of the prepared cubic pomelo peel samples.

After sample preparation, stepwise unconfined uniaxial compression tests were performed on different pomelo peel samples by using the built-in MST loading device (44 N load cell with a maximum displacement of 5 mm) within the Skyscan 1172 desktop X-ray CT system (Bruker Corporation, USA). Before the test, an initial compression load of 10 g was exerted on the test specimen to ensure the stability of stepwise loading and CT scanning. Fig.3 exhibits the experimental protocol including scanning chamber, test sample inside the loading device, the applied displacement-time curve and stress-strain curve for the stepwise uniaxial compression test. During the compression tests, the bottom platen moved upward and top platen kept stationary. The stepwise vertical motions of the bottom platen were preset as 1 to 5 mm at an increment of 1 mm. It took nearly 5 min to move the bottom platen upward to exert the preassigned motion at a displacement rate of $3 \mu\text{m/s}$. After loading, a pause of 10 min was set to address the stress relaxation issue due to the viscoelasticity behavior of the sample and ensure adequate relaxation time of the specimen before CT scan [30]. Afterwards, 500 projection images of the test sample were recorded by the micro-CT system at a spatial sampling grid of 2000×1336 pixels and a spatial resolution of $9.0 \mu\text{m/voxel}$. 180° scan and a rotation step of 0.4° were selected to ensure quick CT scan within 20 min. After short CT scan, the loading-relaxation-scanning process was repeated to record images in the next loading step. Finally, one reference and five deformed volume images with a size of $2000 \times 2000 \times 1040$ voxels were reconstructed by the NRecon software. Note that a series of practical solutions and strategies were employed to minimize image artifacts and eliminate image blur due to possible stress relaxation and motion of the pomelo peel sample during CT scan as reported in existing work [31,32].

More importantly, due to longtime exposure to external environment, the test sample would undergo water-loss shrinkage, resulting in shrinkage strains in three directions. In addition, longtime CT scan would induce considerable self-heating effect and hence uniform dilatational strains in three directions [31,33]. Thus, to remove undesirable deformation associated with water-loss shrinkage and dilatational strain due to self-heating effect and then recover the actual mechanical-induced strains, rescanning tests of pomelo peel sample were necessary [31]. Specifically, a cubic sample (same size as the test sample) cut from the adjacent part of the test sample was prepared, which was used as a reference sample in the rescanning tests. Then, rescanning tests of the stationary reference sample without external loading were performed using the same scanning setting and time interval as the uniaxial compression tests. In this manner, these volume images (i.e., one reference and five distorted volume images) can approximately record the undesirable strains in the compression tests.

Fig.3 Experimental protocol for the stepwise uniaxial compression test: (a) scanning chamber; (b) test sample inside the loading device; (c) applied displacement-time curve; (d) resulting stress-strain curve.

3.2 Image processing and deformation calculation

Based on the reconstructed volume images recorded at different loading steps, ImageJ software [34] was employed to analyze the morphologic features of pomelo peel samples. First, the “Otsu Threshold” function was applied to each slice to distinguish solid and void. In this work, due to the selected spatial resolution during tomographic imaging (i.e., 9 $\mu\text{m}/\text{voxel}$), the foam-like structure and vascular bundles are visualized as material, while biological cells (cell-wall thickness below 5 μm) and pores inside the pomelo peel are specified as void. Then, the “Analyze Particles” function with a reasonable size threshold (100 voxel in this work) was selected to extract vascular bundles within each image slice. Finally, average cell size and cell-wall thickness were assessed by the “BoneJ” plugin [35]. Note that the cell in this work is defined as the visible foam cell of the foam-like microstructure rather than the biological cell.

Image rendering and segmentation were performed using Avizo Fire 8.1 software. The “Edge-Preserving Smoothing” and “Median Filter” functions were first adopted to reduce possible image noise and enhance contrast. Subsequently, segmentation of the tomograms was performed by using a series of modules including “Magic wand”, “Dilation”, “Fill Hole” and “Erosion”. Finally, the “Generate Surface” function along with “Smooth surface” and “Simplification” modules were utilized to extract the morphology of the vascular bundles throughout the uniaxial compression test.

The volume images of the test samples and reference samples acquired at different stages were processed by the advanced DVC approach described above to retrieve internal displacement fields. As shown in Fig.4, both stepwise (incremental) and total (cumulative) strain fields were evaluated. To measure the stepwise displacement fields between adjacent loading steps, the previous volume image was used as the renewed reference volume in each current correlation step. While for total deformation measurement, an improved incremental DVC technique [36] was adopted to deal with the decorrelation effect during large deformation tracking. In DVC analysis, a cubic volume of interest (VOI) comprising regularly distributed 164836 ($=58 \times 58 \times 49$) calculation points with a grid step of 20 voxels and a subvolume size of $41 \times 41 \times 41$ voxels were defined as depicted in Fig.4. Finally, the 3D PLS method [29] with a window size of $11 \times 11 \times 11$ points (corresponds to a local domain of $201 \times 201 \times 201$ voxels) was implemented to extract the internal full-field strains. Note that the global strain components in the rescan tests were

extracted and then used to recover the actual mechanical-induced strains during strain calculation in the uniaxial compression tests.

Fig.4 Schematic diagram showing (a) the calculation procedure and (b) the selected calculation parameters for DVC analysis

3.3 Poisson's ratio measurement

The Poisson's ratio, a measure of the Poisson effect, is the negative ratio of the lateral expansion or contraction of a material to the uniaxial strain. Most materials have Poisson's ratio values ranging between 0 and 0.5. A perfectly incompressible material deformed elastically at small strains would have a Poisson's ratio of exactly 0.5 [37]. In this work, the DVC-measured total strain fields in five different loading stages can be globally averaged to extract three normal strain components. Then, the Poisson's ratio of the pomelo peel sample in the stepwise uniaxial compression test can be evaluated as [38]

$$\mu_{xz} = -\frac{\varepsilon_x}{\varepsilon_z} \quad \mu_{yz} = -\frac{\varepsilon_y}{\varepsilon_z} \quad (4)$$

where ε_x , ε_y and ε_z are the average normal strains in x , y and z directions.

4. Results

4.1 Microstructure visualization

Fig.5 exhibits the rendered tomographic images of a pomelo peel sample recorded by the X-ray micro-CT system. In these graphs, each discrete bright spot represents one single foam cell with the brightness of the spot denoting the size of the foam cell. It can be observed that the internal microstructure of the pomelo peel sample, varying from exocarp to endocarp, is a hierarchical foam-like structure permeated by vascular bundles (here it refers to the clusters of thick branching structure rendered in black) with diverse sizes and connected by foam cells (here it refers to the cell of foam-like structure rather than the biological cell) with varying cell spaces. The slice located in exocarp includes plenty of randomly distributed small vascular bundles surrounded by densely packed foam cells. In contrast, the vascular bundles within the endocarp, connected by a series of larger foam cells, are relatively thicker and sparsely distributed.

Fig.5 Rendered tomographic images of the pomelo peel sample extracted from different slices.

Fig.6 illustrates major microstructure features including volume fraction, bundles number, cell size (referred as foam cell) and cell-wall thickness within each tomographic image of a stationary pomelo peel sample. It is observed that the porosity of the pomelo peel rapidly increases first and then slowly declines from exocarp to endocarp within a range of 60% to 85%. The location of maximal porosity is at 1/3 distance from the exocarp while the minimal porosity appears in the domain close to the exocarp. The outer 1/6 part of the pomelo peel has a denser structure with higher bundles volume fraction, while the inner 5/6 part shows sparser bundles distribution. It is worth noting that pomelo peel samples cut from distinct regions show similar distribution of bundles number from exocarp to endocarp, namely, significant decrease in the outer 1/6 region and slow decline in the rest 5/6 region. The bundles number per square millimeter is almost at a range of 0.1 to 0.9 from endocarp to exocarp. Since vascular bundles are more resistant to the compressive force than the surrounding foam-like tissue, smaller normal strain in exocarp (bottom slices) can be expected in the following uniaxial compression test.

Fig.6 also indicates that average cell-wall thickness within each slice ranges from 5 to 7 voxels (45 to 63 μm), and average cell size has a range of 7 to 17 voxels (63 to 153 μm) from exocarp to endocarp. Their peak values are present at nearly 2/5 distance from the exocarp while minimal values located in exocarp. Likewise, from the cell size distribution along z direction, it can be reasonably predicted that mesocarp and endocarp (i.e., middle and top slices) may undergo larger strain than the exocarp (bottom slices) in response to compressive loading.

Fig.6 Morphological parameters of pomelo peel sample: (left) volume fraction, (middle) bundles number, (right) foam cell geometry.

4.2 Morphological change

Fig.7 presents the volume renderings of the vascular bundles within a pomelo peel sample at different loading stages. It is shown that the vascular bundles are interconnected and displayed as a dendritic structure with stochastic void. The bundles within endocarp (upper domain of the reconstructed model) shows a sparse distribution, while the exocarp (lower domain of the reconstructed model) exhibits more branches of bundles. The high density of the vascular bundles within exocarp leads to high resistance to compression compared with the endocarp. As the compressive strain increases from 0 to 10%, bundles bending can be first observed within endocarp, and then

occurs in the mesocarp under higher compressive strain. These morphological variations are in accordance with the evolution of total strain fields described in Section 4.3. Bundles bending occurs at various applied strains mainly due to a wide variety of bundles diameters and distributions. The stepwise compaction process gradually densifies the whole pomelo peel sample, especially the relatively sparse domain. Following this trend, the sample finally may tend to homogenization and densification at very high compressive strain.

Fig.7 Morphological evolution of vascular bundle within pomelo peel at different compressive strains.

4.3 Internal deformation measurement

Fig.8 displays the 3D total w displacement and ϵ_z strain fields measured by the incremental DVC approach [36] in the stepwise uniaxial compression test of the pomelo peel sample. It is seen that the measured total w displacement fields in the five loading stages exhibit a significant feature of upward compression as expected from the loading configuration shown in Fig.3, but the compressive displacements show non-uniform increase from endocarp (top slices) to exocarp (bottom slices). The measured normal strains ϵ_z indicates significant gradient along z direction, especially in the region close to the exocarp. Furthermore, the DVC-measured total strains fields also show significant nonuniformity in xoy plane, and relatively small deformations occur close to vascular bundles within each slice.

Fig.8 DVC-measured total w displacement fields (unit: voxel, voxel size: $9.0 \mu\text{m}/\text{voxel}$) and total ε_z strain fields in the stepwise uniaxial compression test of the pomelo peel sample.

As shown in Fig.7, the endocarp has larger porosity than the mesocarp at first, but become denser during the test due to larger deformation in the first loading stage. As such, endocarp (top slices) tend to show stronger resistance to compression than the mesocarp (middle slices) in the second loading stage, and hence the high strain domain gradually moves from endocarp to mesocarp in the last four loading stages. By comparing the morphological changes of vascular bundles with DVC-measured deformation fields, it can be found that the in-plane (xoy plane) and z -directional nonuniform strains basically agree with the bundles distribution in each loading stage.

4.4 Morphology-mechanics relationship

After obtaining the stepwise full-field deformations via DVC, the average stepwise w displacement and ε_z strain along with the above-mentioned four microstructural features within each slice were estimated. Fig.9 exhibits the average morphological parameters and stepwise deformations in each tomographic image of the pomelo peel sample under different compressive strains. It can be observed that bundles volume fraction within each slice increases with the compressive strain. The average bundles number and cell size along z direction tend to show smaller value ranges as the applied strain increases. In the five loading stages, the stepwise w displacements along z direction are almost in a range of 8 to 106 voxels (72 to 954 μm), and the stepwise ε_z strains in different slices vary from 1% to 18%. More importantly, as the imposed loading increases, the value range of the stepwise ε_z strain along z direction decreases from 15% (from 2% to 17% in stage 1) to 4% (from 14% to 18% in stage 5), which means the differences in resistance to compression of different slices are narrowed. In addition, the location of the maximum strain gradually moves from endocarp (stage 1) to mesocarp (stages 2 to 5), which agrees well with the evolution process of bundles bending described in Section 4.2.

More importantly, by comparing the three graphs in each loading step, the relationship between morphological features and mechanical responses can be observed. Initially, dominated by the bundles volume fraction, large strain domain (larger than 10%) appears in endocarp (top slices) although the maximum foam cells locate in mesocarp in the first loading stage. In stages 2 and 3, the differences in bundles volume fraction within endocarp and mesocarp are narrowed, thus large strain domain spreads to mesocarp because of larger cell size. Lastly, the large strain domain further moves toward the mesocarp, and almost all the slices undergo compressive strain larger than 10% in stages 4 and 5. Especially, since the morphological parameters show much less fluctuation along z direction, the average ε_z strains within different slices tend to exhibit much less value range (4%) in the 5th stage. Therefore, bundles volume fraction and foam cell size can be referred as two major factors governing strain distribution of pomelo peels from exocarp to endocarp under compaction.

Fig.9 Morphological parameters and stepwise deformation of the pomelo peel sample in each loading step of the uniaxial compression test.

Likewise, the average total w displacement and ε_z strain within each slice are calculated based on the DVC-measured displacement and strain illustrated in Fig.8. In addition, the changes in bundles volume fraction and foam cell size with respect to initial counterparts are estimated. Fig.10 displays the average total w displacement and ε_z strain along with the changes in bundles volume fraction and foam cell size in each slice. In the graphs, the distribution of total ε_z strain along z direction is always a concave curve, and the location of maximal total ε_z strain gradually moves from endocarp to mesocarp as the imposed loading increases. Following the total strain evolution, the changes in bundles volume fraction and foam cell size along z direction also exhibit as curvature curves, and the maximal variations also move towards exocarp in response to increasing load.

Fig.10 Total w displacement and ε_z strain as well as changes in bundles volume fraction and foam cell size along z direction under five different applied strains.

To better understand the relationship between DVC-measured deformation response and morphological evolution at each volume slice of the pomelo peel samples during compaction, the data in Fig.10 are replotted to exhibit the changes in bundles volume fraction and foam cell size as a function of absolute DVC-measured total ε_z strain in five different loading stages, as shown in Fig.11. It is seen that bundles volume fraction increases almost linearly with the increase of the DVC-measured total compressive strain. As a matter of fact, the densification of the pomelo peel and the decrease of porosity subjected to large compressive strains can be viewed clearly from Fig.7. To follow this trend, the average foam cell size decreases linearly as DVC-measured compressive strain increases.

Fig.11 Changes in bundles volume fraction and foam cell size as a function of absolute DVC-measured total ε_z strain in five different loading stages.

4.5 Poisson's ratio

Fig.12 illustrates the uncorrected and corrected (by rescan tests) strain components estimated by DVC method and the Poisson's ratio in different loading stages. Despite the fact that pomelo peel sample would undergoes lateral expansion during z -directional compression, the DVC-measured lateral strains are always negative and decrease with the increasing applied strain. In fact, the directly measured negative lateral strains mainly comprise the drying shrinkage strains of the pomelo peel samples exposed to air. By subtracting the global shrinkage strains extracted from the rescan tests, the corrected counterparts show reasonable lateral expansion of the sample in response to vertical compression. To be specific, the lateral strains increase from -2.9% to 5.4% under an applied strain of 50% after correction. In the final loading stage, the CT tube basically reach thermal stabilization according to a priori knowledge of the X-ray CT system, and the final dilatational strain due to self-heating effect is nearly 350 μe [33,39], which is marginal compared with the shrinkage strain due to water-loss shrinkage. As can be deduced from the left part of Fig.12, the shrinkage strains in x and y directions, linearly increasing with the stepwise loading, are almost identical and reach a magnitude of nearly 8.3% in the final loading stage. The standard deviations of the DVC-measured lateral strains increase with the imposed strain due to the error accumulation during displacement tracking. From the right part of Fig.12, we can see that the Poisson's ratio of pomelo peel sample, varying from 0.08 to 0.11 with a SD of 0.02, is much more reliable after correction. It also can be seen that the Poisson's ratio of pomelo peel sample remains low at first due to high compressibility and increases at moderate strains as the sample becomes compacted.

Fig.12 DVC-measured strain components before and after correction as well as Poisson's ratio in different loading stages.

5. Conclusion

In this work, stepwise uniaxial compression tests of pomelo peel samples were performed to understand the relationship between mechanical properties and microstructure features of pomelo peel. In-situ X-ray tomographic imaging technique and DVC approach were employed to quantify its morphological changes and full-field internal deformations during compression. Through X-ray tomographic imaging, it is revealed that the distribution of microstructure features including volume fraction, bundles number, cell-wall thickness and foam cell size show significant variations from endocarp to exocarp, thus exhibiting diverse resistance to compression along z direction. As the imposed loading increases, bundles bending was first observed within endocarp and then occurs in the mesocarp, which is in accordance with the deformation evolution process characterized by DVC approach. Using DVC, 3D stepwise and total ε_z strain fields at different loading steps were extracted and averaged in xoy plane. It is shown that, as the applied load increases, large strain domain gradually moves from endocarp to mesocarp, and the stepwise ε_z strains tend to show less value range. The total ε_z strain fields show significant non-uniformity within xoy plane and along z direction, which agrees with the distribution of vascular bundles. In addition, the Poisson's ratio values determined by DVC remain low at first and then increase at moderate strains, which is related to its compressibility during stepwise compression. By connecting morphological evolution and quantitative internal deformation analysis, bundles volume fraction and foam cell size are identified as two major factors affecting strain distribution along z direction. Total ε_z strains and the changes in the two factors exhibit similar distributions along z direction throughout the compression test. More interestingly, the correlation between total ε_z strains and the variations of these two morphological features is approximately linear in the five loading stages.

The cellular architecture within pomelo peel provides outstanding properties like damping capacity or efficient energy absorption as the hierarchical structures can be compressed over a wide strain range at plateau stress. There are two strategies for transferring natural microstructure features into biomimetic structures in industrial design [10]. The first strategy is to mimics the open cellular structure since the gradient of its intercellular space contributes to its outstanding energy absorption capability. The other scheme takes advantages of the lignified and branched vascular bundles to provide mechanical support and distribute locally induced forces into larger volumes of the peel.

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Graphical abstract

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.