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Multiscale characterization of deformation mechanisms in cork under compression using Digital Image Correlation and X-ray tomography

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Abstract – While the macroscopic behavior of cork-based material is well established, the underlying deformation mechanisms remain poorly understood due to its multiscale heterogeneity. This study combines Digital Image Correlation (DIC) and in situ X-ray microtomography to investigate deformation in natural and agglomerated cork under compression. Mesoscale measurements reveal highly heterogeneous strain fields characterized by localized compression bands and extensive low-strain regions that remain nearly undeformed throughout loading. At the microscale, X-ray microtomography reveals progressive cell wall buckling followed by localized densification of the cellular network.

Keywords – Cork, Digital Image Correlation, X-ray tomography, full-field measurement

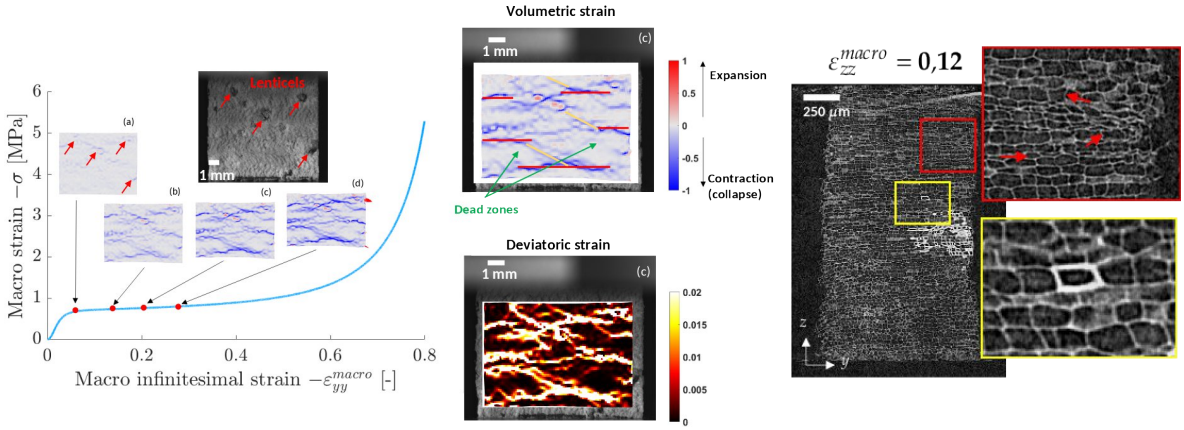
Introduction

Cork is a bio-based cellular material widely used in applications such as wine stoppers, insulation systems, and lightweight structures due to its unique properties, including thermo-acoustic insulation, impact resistance, and barrier capabilities. Its compressive stress–strain response is well known and typically described by three stages: linear elasticity, a plateau associated with cell wall buckling, and densification. However, this macroscopic description assumes a homogeneous material and neglects the intrinsic heterogeneity of cork, which exhibits a complex multiscale structure. At the mesoscale, features such as lenticels or grain boundaries introduce heterogeneities, while at the microscale, cork consists of closed cells with anisotropic geometry and variable wall thickness [1]. Establishing the link between this hierarchical structure and the mechanical response is therefore essential. Despite its strong relevance for Digital Image Correlation (natural speckle, large strains, heterogeneous deformation), cork has been only sparsely studied using full-field measurements. Previous works revealed heterogeneous strain fields under compression [2-4], but the link to deformation mechanisms at the microscopic scale has not yet been clearly established. The objective of this study is to characterize cork deformation under compression by linking mesoscale strain fields obtained by DIC with microscale structural evolution observed through X-ray tomography.

Methods For mesoscale characterization, quasi-static compression tests were performed on centimetric cubic samples of natural and micro-agglomerated cork. The sample surfaces were prepared with a stochastic speckle pattern to enable DIC measurements. Images were acquired during loading and processed to compute displacement and strain fields. A global approach DIC was performed using UFreckles. To investigate deformation mechanisms at microscale scale, cylindrical samples of approximately 1 mm diameter were extracted and subjected to in situ compression inside an X-ray microtomograph. This setup enabled 3D imaging of the innner structure at different loading stages. Image processing was performed to segment the cellular network and quantify the evolution of porosity profil during compression.

Results DIC measurements reveal a highly heterogeneous strain field in both natural and agglomerated cork samples. Deformation localizes into well-defined compression bands, mainly oriented transverse

to the loading direction, and to a lesser extent in oblique directions. In natural cork, strain localization preferentially initiates near lenticels, highlighting their role as structural weak points and thus as mesoscale stress concentrators (Figure 1-a). In contrast, agglomerated cork exhibits a larger number of thinner compression bands, suggesting a more distributed initiation of deformation. Additionally, regions with very low strain, referred to as “dead zones” are observed, indicating that deformation is not uniformly distributed and is instead carried by specific localized areas. X-ray tomography provides direct insight into the evolution of the cellular structure during compression. The main deformation mechanism identified is the progressive buckling of cell walls, which occurs heterogeneously throughout the sample, and governs the plateau regime of the macroscopic response. Buckling initiates at different strain levels and depends strongly on local cellular morphology. Some regions exhibit early collapse, while others remain nearly undeformed at the same global strain level. Porosity analysis reveals that densification first occurs at the sample ends before propagating toward the core. This behavior is attributed to the presence of weakened areas, possibly induced during sample preparation, and to the intrinsic variability of the cellular network.



(a) (b)

Figure 1: (a) Response curve of natural cork, with strain field measurements. (b) Cell wall buckling observed using X-Ray tomography.

Discussion and Conclusion The combined use of DIC and X-ray microtomography provides a comprehensive multiscale understanding of cork deformation under compression, with direct experimental link between mesoscale strain localization and microscale deformation mechanisms. At the mesoscale, the deformation field is shown to be highly heterogeneous, characterized by compression bands and dead zones. At the microscale, this behavior is explained by localized cell wall buckling and spatially heterogeneous densification. These findings highlight the key role of structural heterogeneities, such as lenticels in natural cork or defects introduced during manufacturing, in controlling the deformation localization.

Open Science The post-processing of experimental data was performed exclusively using open-source codes.

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