Understanding deformation mechanisms of cork under compression loading using Digital Image Correlation

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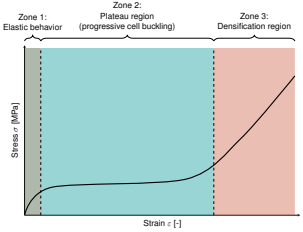
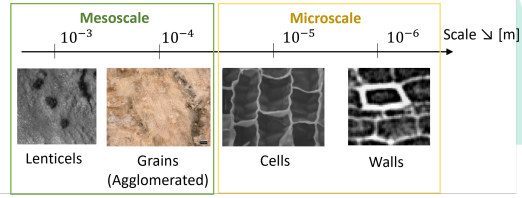
Scientific context

Compressive behavior of cork materials



Assumption of homogeneous medium.
$\Rightarrow$ no microstructure consideration.

Multiscale structure of cork materials



The microstructure of cork is at the root of its properties.
... How does the microstructure evolve during cork compression?

Problematic

Understanding **links** between **macroscale mechanical behavior** and **microstructure evolution**.

Approach

Multiscale experimental approach:
$\Rightarrow$ **mechanical tests** + **Digital Image Correlation** (DIC) and **X-ray tomography**.

Outline

Experimental setup

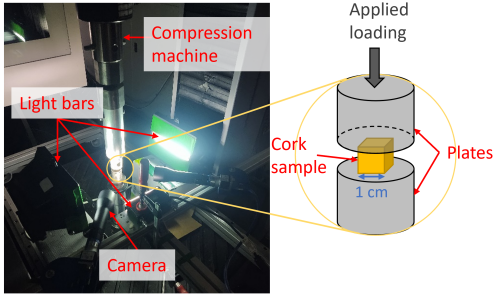
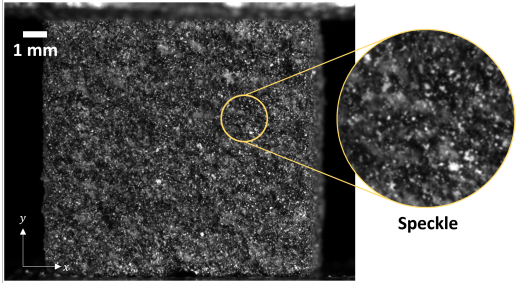
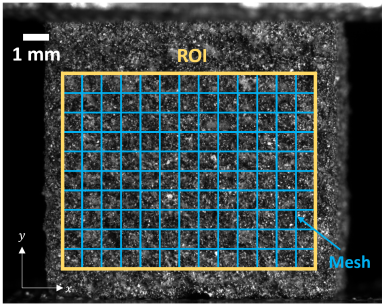


Image of the sample surface in its initial state

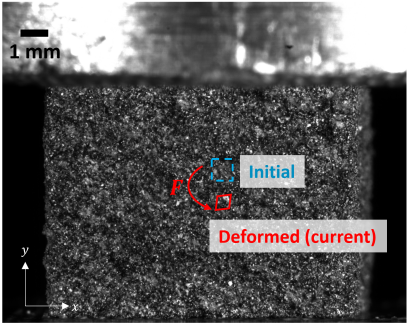


- Compression tests with DIC setup,
- Speckled samples ⇒ generate patterns and enhance contrast.

Initial state

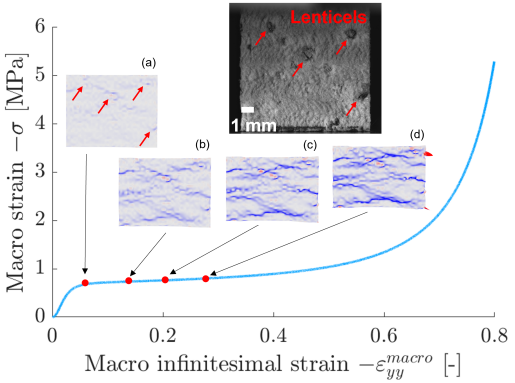


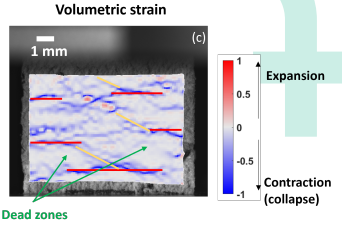
Deformed state



- Displacement field measurement by mean of pattern tracking on a mesh defined in a Region of Interest (ROI), leads to deformation gradient tensor $\boldsymbol{F}$ for each element of the mesh.
- Hencky strain : $\varepsilon_h = \frac{1}{2}\ln(\boldsymbol{F}^\top \boldsymbol{F}) = \varepsilon_h^{vol} + \varepsilon_h^{dev}$
  ε_h^{vol} : **Volumetric strain** $\Rightarrow$ **"volume change"**
  ε_h^{dev} : **Deviatoric strain** $\Rightarrow$ **"shape change"**

Mesoscale analysis / Strain localization in natural cork under compression



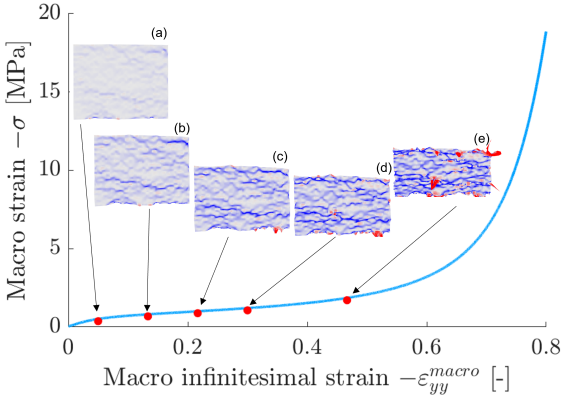


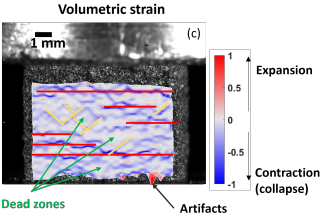
- **Highly heterogeneous** strain field,
- **Strain localization starts close to lenticels**,
- Propagation in **transverse and oblique bands**,
- Presence of **"dead zones" which do not participate to strain**,
- Volume and shape change of (very) strained zones.

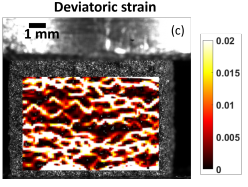
Based on the experiments in:

Gerometta et al. (2023) "Towards better understanding of the strain–stress curve of cork", *Material & Design*

Mesoscale analysis / Strain localization in micro-agglo. cork under compression

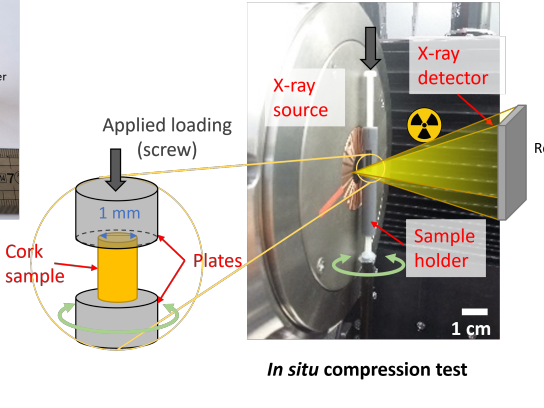






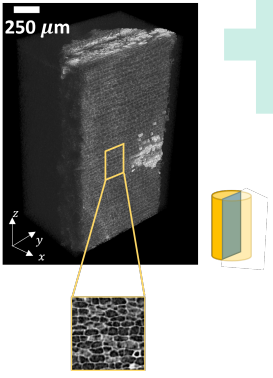
- **Highly heterogeneous** strain field with same pattern (bands + dead zones),
- Larger number of compression bands

Microscale analysis / *in situ* micro-compression tests in X-ray tomograph



In situ compression test

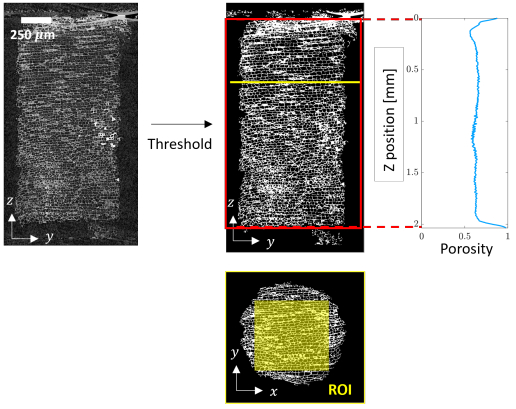
3D Reconstruction



- Extraction of 1 mm wide cylindrical sample of natural cork using micromilling,
- In-situ compression tests with X-ray tomography.

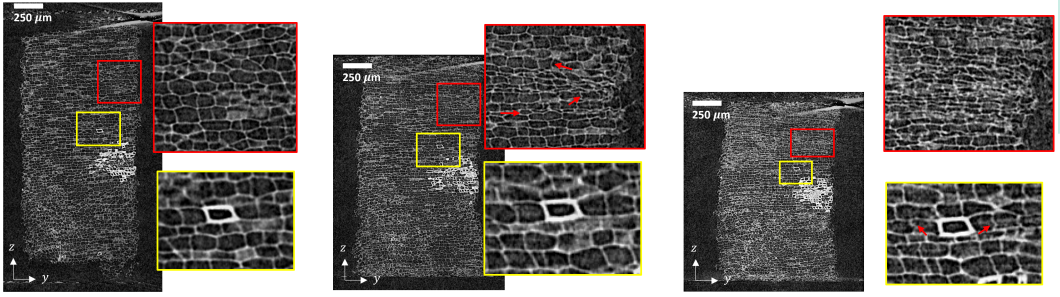
⇒ **Inner cork structure (cell scale) and its evolution during compression**.

Microscale analysis / Porosity profile



- Porosity : $\rho = 1 - \frac{V_w}{V_{tot}}$
  with V_w : Volume of cell walls (white voxels) and V_{tot} the total volume,
  - $\rho = 0 \Rightarrow$ fully **dense** material,
  - $\rho = 1 \Rightarrow$ fully **void** material.
- Evolution of porosity along z-axis.
  $\Rightarrow$ Porosity profile.

Microscale analysis / Progressive buckling of cell walls



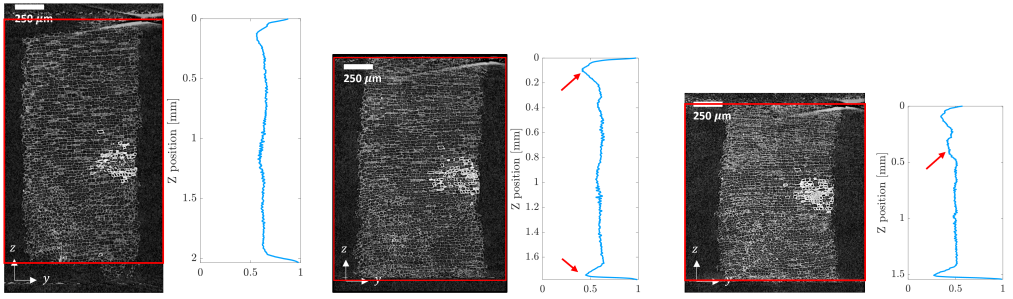
Step 0
Initial state

Step 1
$\varepsilon_{zz}^{macro} = 0{,}12$

Step 2
$\varepsilon_{zz}^{macro} = 0{,}24$

- **Direct observation** of cell wall buckling,
- **Localized buckling** : Zones fully collapsed and zones with limited (or no) buckling,
- **Onset of buckling** at different levels of deformation depending on the area.

Microscale analysis / Porosity profile evolution under compression



Step 0
Initial state

Step 1
$\varepsilon_{zz}^{macro} = 0{,}12$

Step 2
$\varepsilon_{zz}^{macro} = 0{,}24$

- **Densification starts at top and bottom** of the sample,
- Probably due to creation of **weak zones** during micromilling,
- **New densification zones appears** as well as loading increases.

Conclusions and perspectives

Key points

- At **mesoscale**, micro-agglo. and natural cork samples exhibit:
  - **highly heterogeneous strain field**,
  - transverse and obliques **compression bands**,
  - **dead zones** with very little deformation.
- For natural cork, **localization starts close to lenticels**,
- At **microscale**, cell wall **buckling starts at the top and bottom** of the sample, **new densification zones then after appears** with increasing load.

$\Rightarrow$ **The heterogeneity of strain field is probably driven by weak points that are naturally present or introduced during the manufacturing process.**

Outlook

- Which **microstructural parameter**(s) determines the onset and propagation of compression bands?
- How does the **manufacturing process** influence deformation mechanisms?
- What is the **impact of the strain heterogeneity on the diffusion properties** of the stopper?

Thank you for your attention !

Acknowledgments

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