Determination of Drying Stresses in Wood Utilizing the Enhanced Digital Image Correlation (EDIC) Technique

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Introduction

- Drying stress and quality degradation
- Theoretical models for wood drying need experimental support not just at macroscopic but also at microscopic level.
- Conventional experimental techniques for wood shrinkage are not for internal deformation measurement.

Thus,

A new framework for the determination of drying stresses in wood is necessary!

- A new experimental technique for wood drying

  → **The EDIC technique**

- Combine necessary components for the determination of drying stresses in wood

  → **Internal Deformation Analysis System (IDEAS)**

A New Framework

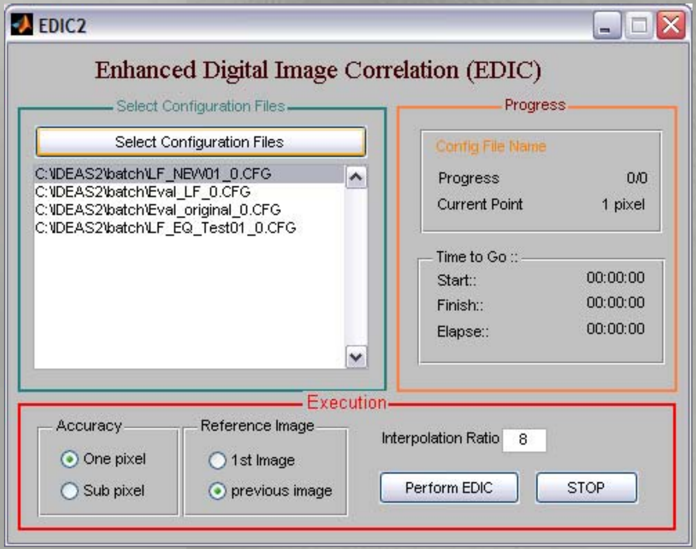
- Internal deformation field: drying strain
  - the EDIC technique
  - non-contact and non-destructive method
- Local moisture content
  - moisture transfer simulation in IDEAS
  - continuous weight measurement
- Local material properties
  - laminate plate theory for cell wall properties in IDEAS
  - image processing for local properties in IDEAS

The EDIC technique

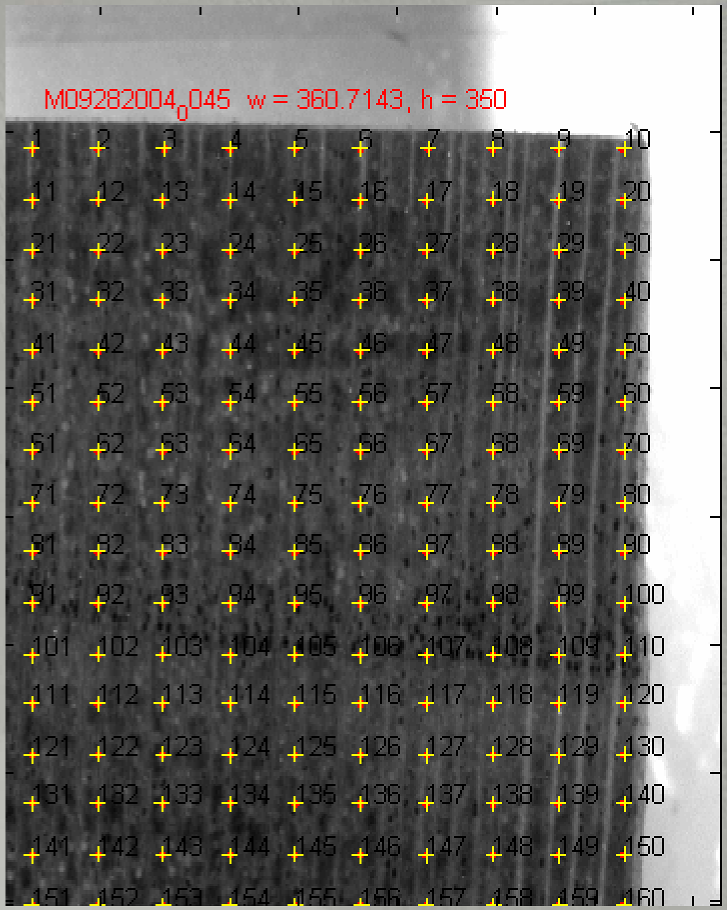
- **Improvement of the DIC technique**
  - **Increase the tolerance against changes in illumination conditions**
  - **Increase the applicable range of moisture content**
- **Low Frequency Tracking (LFT) algorithm**
  - **Low frequency of an image is not sensitive to the changes in illumination conditions.**
- **Fast Normalized Cross-Correlation (FCC) algorithm**
  - **Essentially identical to NCC algorithm, but faster**
- **Interpolation for subpixel accuracy**
  - **A cubic interpolation algorithm**
  - **Accuracy: 0.25 pixel**

Deformation Field by the EDIC

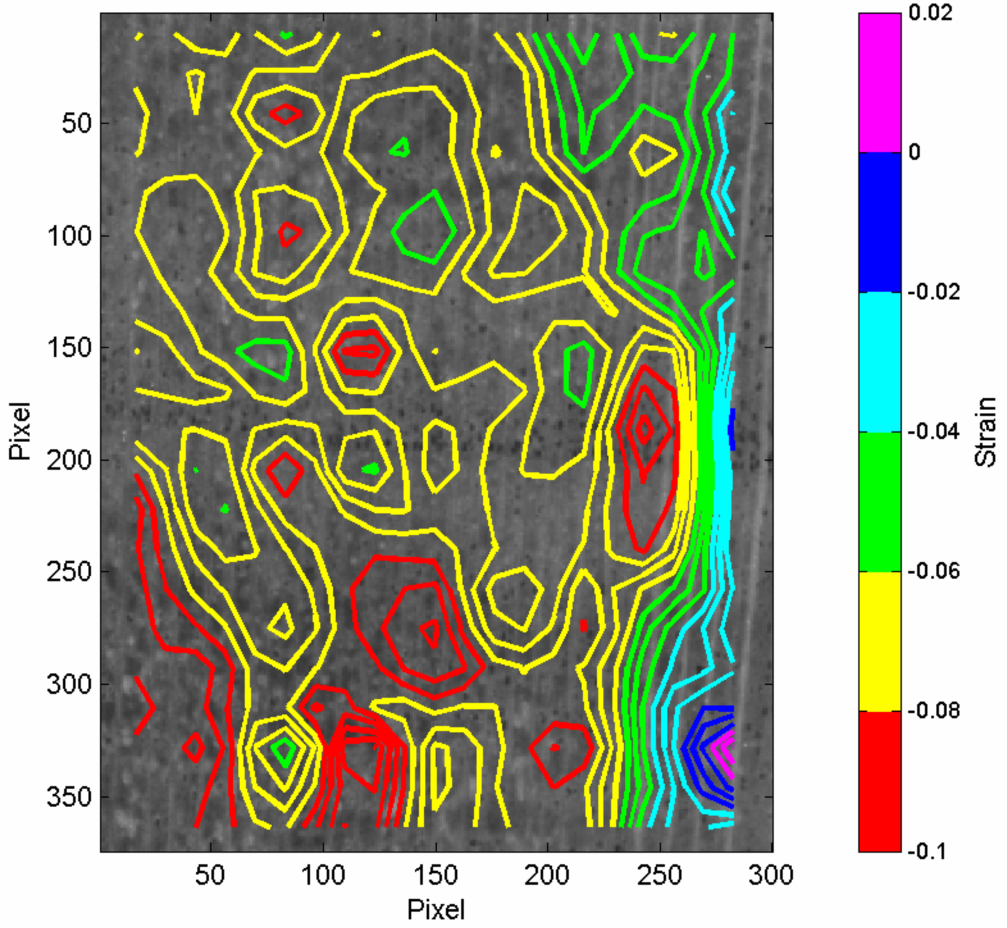
EDIC program



+ reference points; · tracking results



Total Drying Strains by the EDIC



Elastic Strain

Interval elastic drying strain

$$\boldsymbol{\varepsilon}_{elastic}(\Delta t) = \boldsymbol{\varepsilon}_{total}(\Delta t) - \boldsymbol{\varepsilon}_{shrinkage}(\Delta t)$$

measured by the EDIC technique

Interval shrinkage strain

$$\boldsymbol{\varepsilon}_{shrinkage}(\Delta t) = \alpha \cdot \Delta t$$

drying time to generate the total strain

$$\text{where } \Delta t = \frac{t_d}{n} \text{ and } \alpha = \frac{\mathbf{S}}{t_d}.$$

global shrinkage

time interval

shrinkage strain rate

Moisture Profile Simulation

Element matrix

$$\mathbf{K}^e = \int_{\Omega^e} \left(\frac{\partial w}{\partial x}\frac{\partial u}{\partial x} + \frac{\partial w}{\partial y}\frac{\partial u}{\partial y} \right) d\Omega$$

Element matrix for temporal variation

$$\mathbf{M}^e = \frac{A}{36}\begin{bmatrix} 4 & 2 & 1 & 2 \\ 2 & 4 & 2 & 1 \\ 1 & 2 & 4 & 2 \\ 2 & 1 & 2 & 4 \end{bmatrix}$$

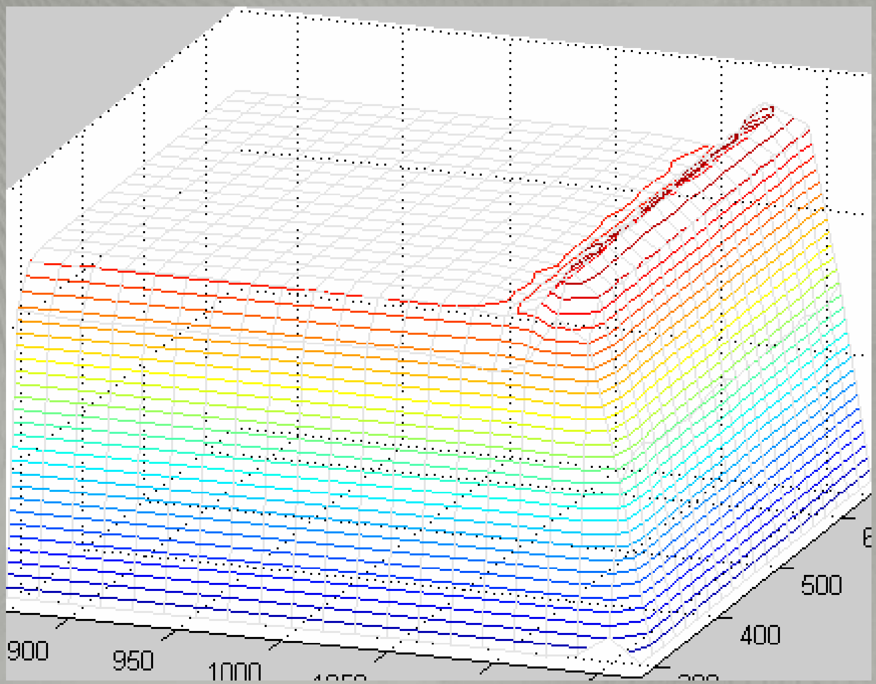
$$u(x, y, t) = \sum_{i=1}^{n} H_i(x, y) u_i(t)$$

Final matrix equation

$$\mathbf{M} \cdot \dot{\mathbf{u}}^t + \mathbf{K} \cdot \mathbf{u}^t = \mathbf{F}$$

Moisture Profile Simulation

Center of the sample



Tangential surface

Radial surface

Calculation of Local Mechanical Properties

$$E_{ij} = \sum_{k=1}^{n} \left(\bar{Q}(X)\right)_k t_k$$

E_{ij} the final laminate stiffness matrix of the cell wall in global coordinates

$\bar{Q}(X)$ the transformed stiffness of an individual layer k in global coordinates

t_k the thickness prescribed based on the experimental result from other literature

$$\mathbf{E}_m = r \cdot \mathbf{E}_c$$

E_c the elastic properties of the cell wall in the local region

E_m the elastic properties of the local region

Determined by image processing techniques

$$r = \frac{A_c}{A}$$

r the correction factor

A_c the area of the cell wall in the local region

A the total area of the local region

Drying Stress Formulation

Determined utilizing the measured internal deformation field

$$\boldsymbol{\sigma} = \sum_{i=1}^{n} \mathbf{E}(X(\Delta t \cdot i)) \cdot \boldsymbol{\varepsilon}_{elastic}(\Delta t)_i$$

From the moisture profile simulation

Determined local elastic properties

$\boldsymbol{\sigma}$ the total drying stress inside the wood

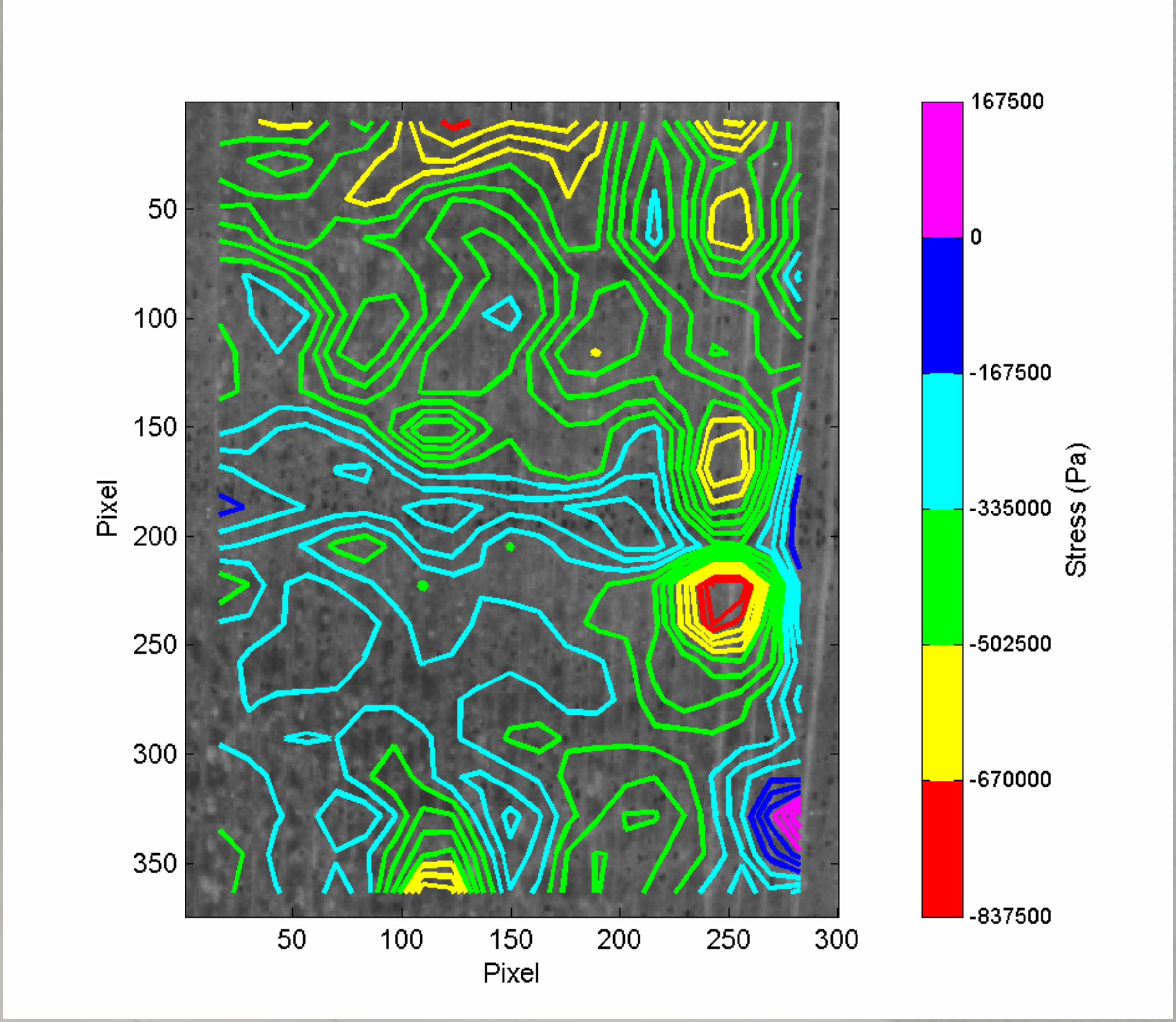
$\boldsymbol{\sigma}(\Delta t)$ the interval drying stress

i the observation index

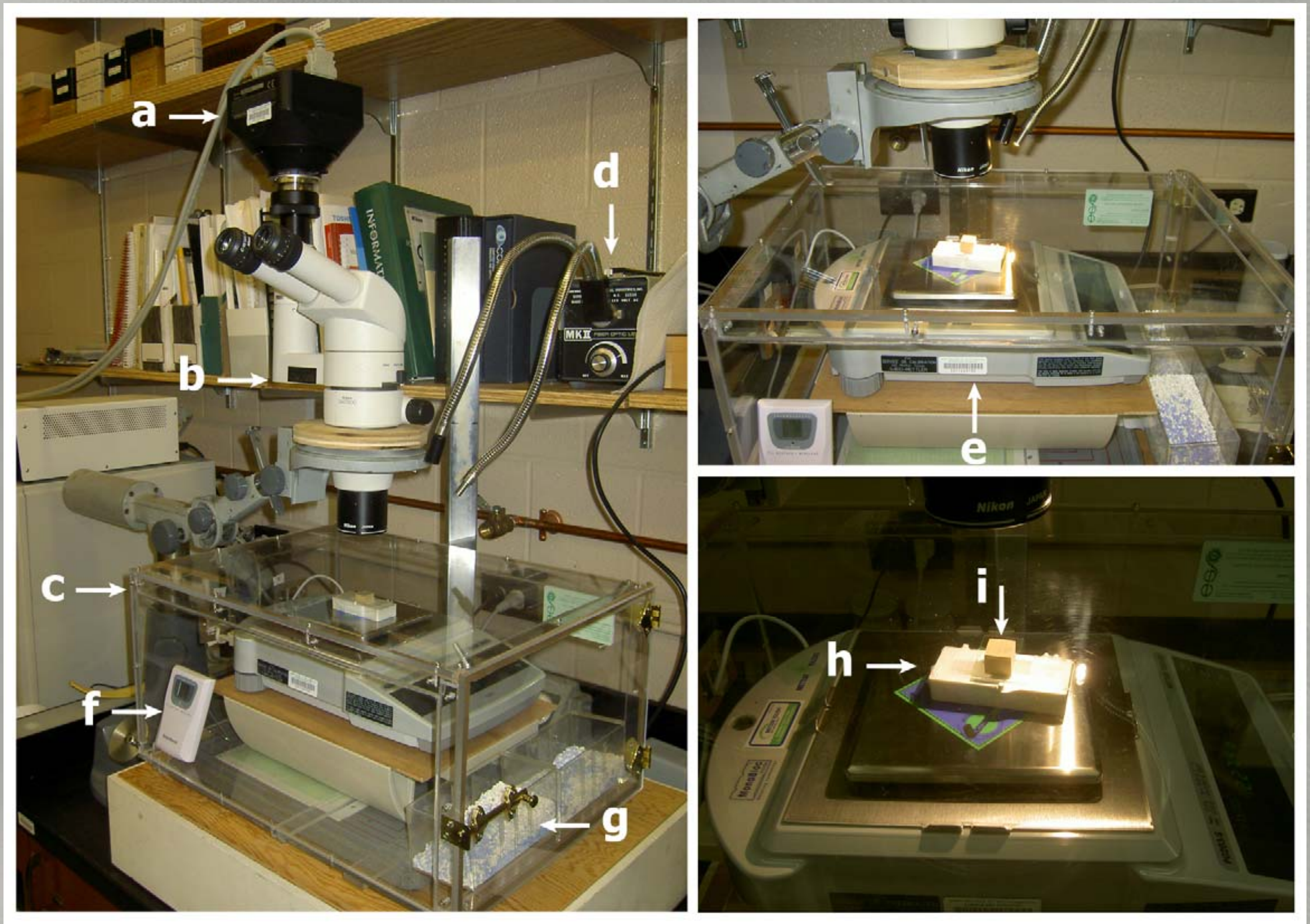
$\mathbf{E}$ the material property of the wood,

$X(\Delta t \cdot i)$ the moisture content of the wood at time $\Delta t \cdot i$

Example::Drying Stress

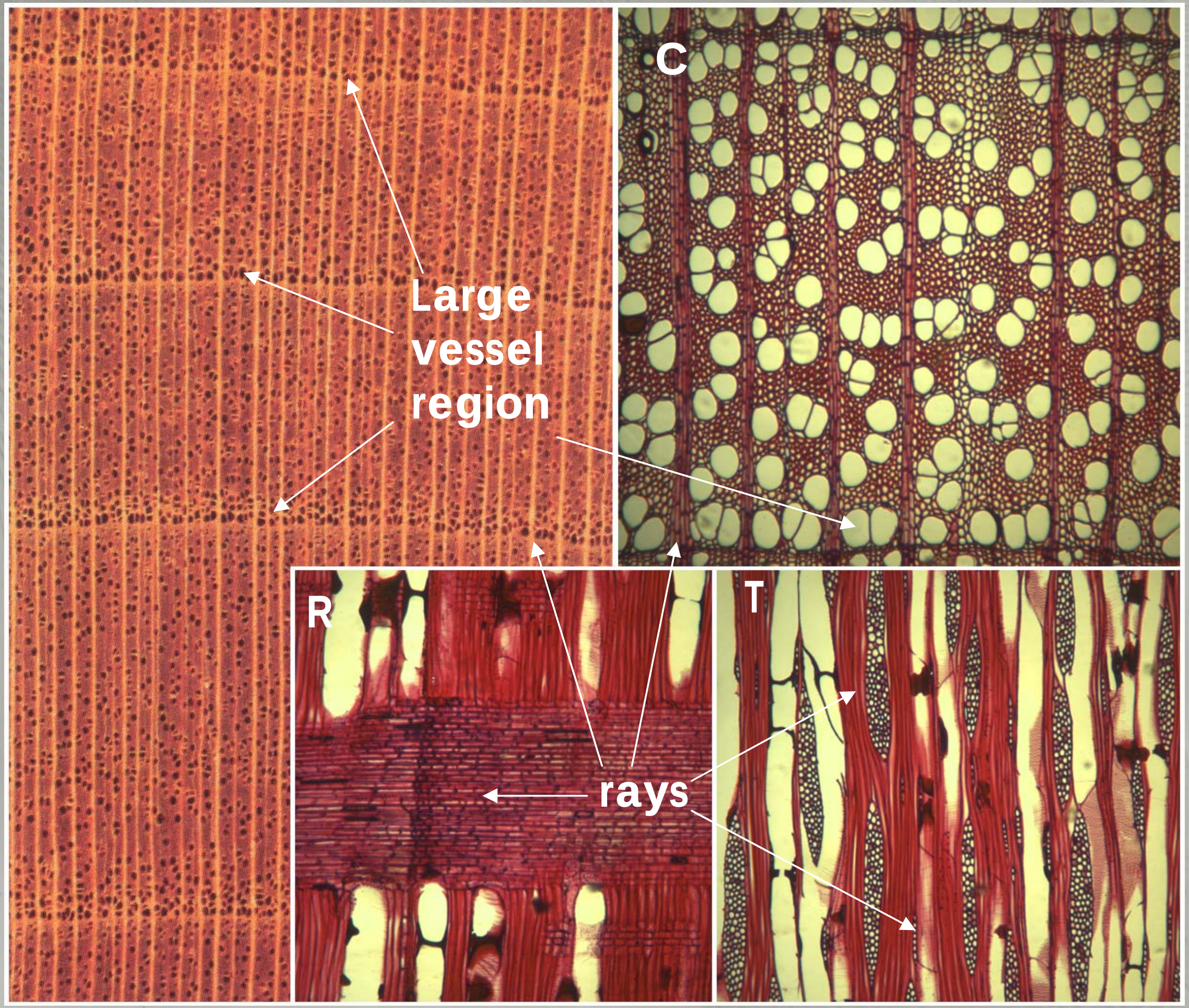


Drying Stresses in Real Sample

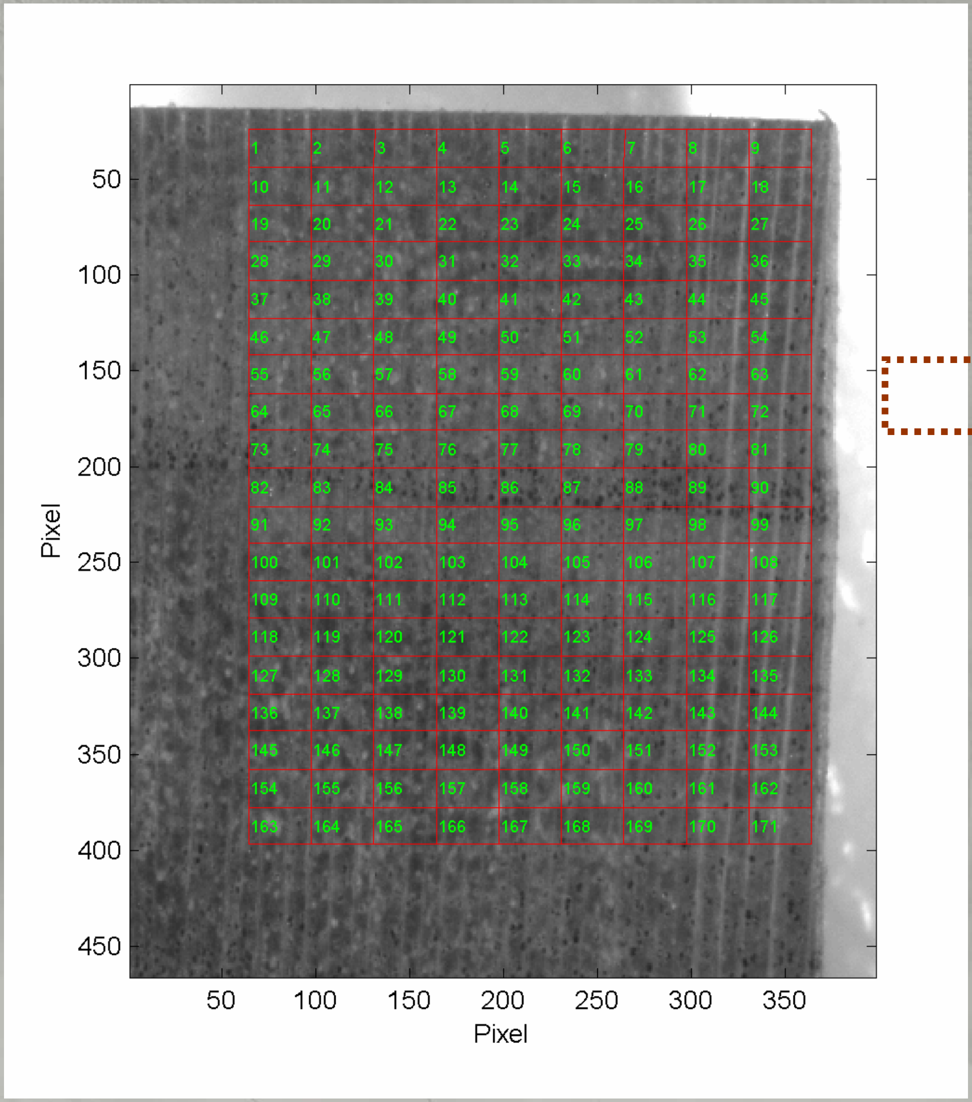


Sample::Black Cherry

- **Black cherry (*Prunus serotina*)**
  - **Hardwood**
  - **Diffuse to semi-diffuse porous wood**
  - **Uniform distribution of rays**



Grid for Investigation

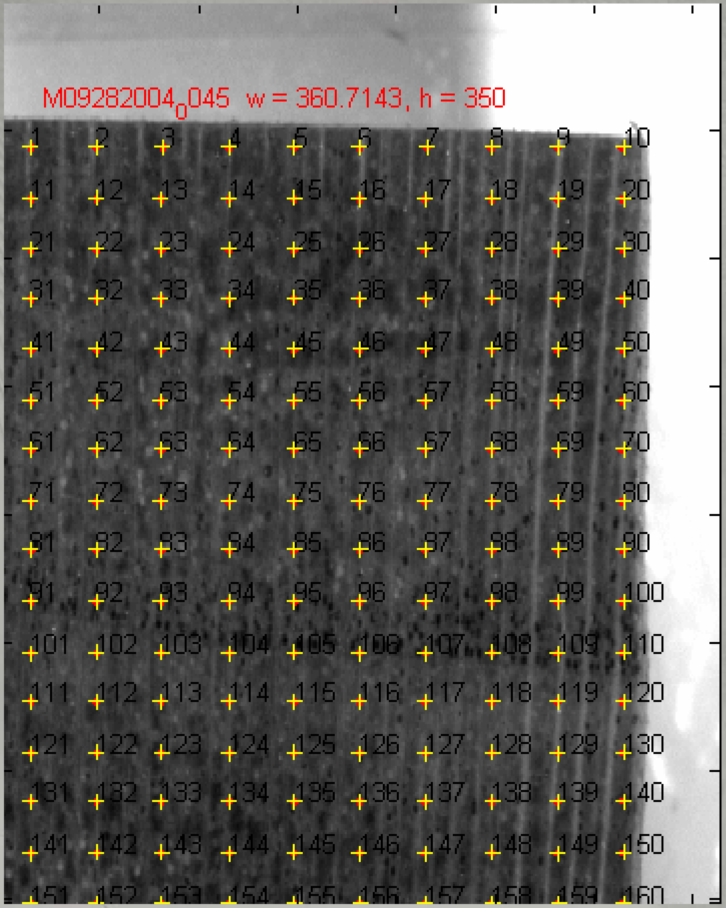


EDIC Technique

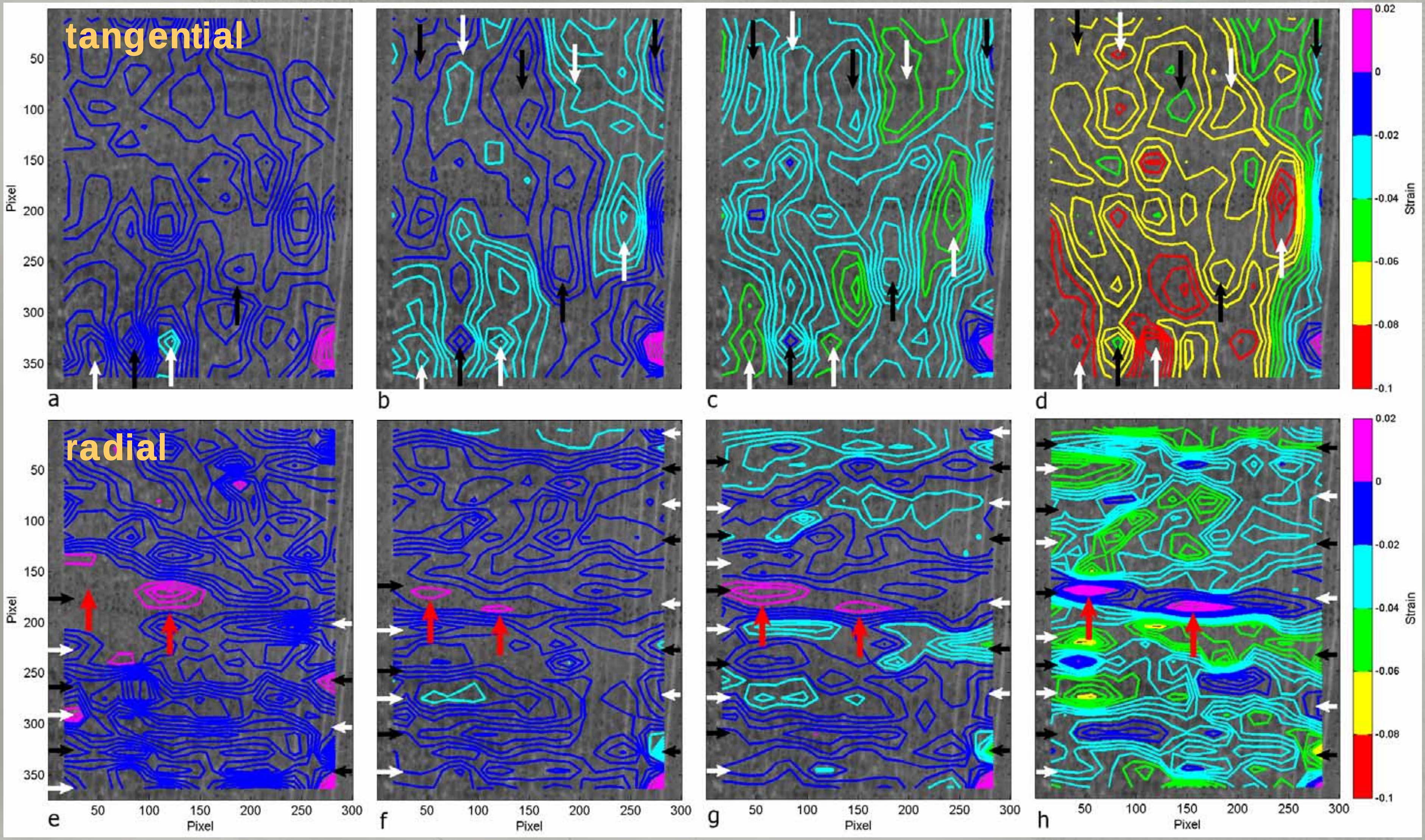
MC Simulation

Tracking Result

+ reference points; · tracking results



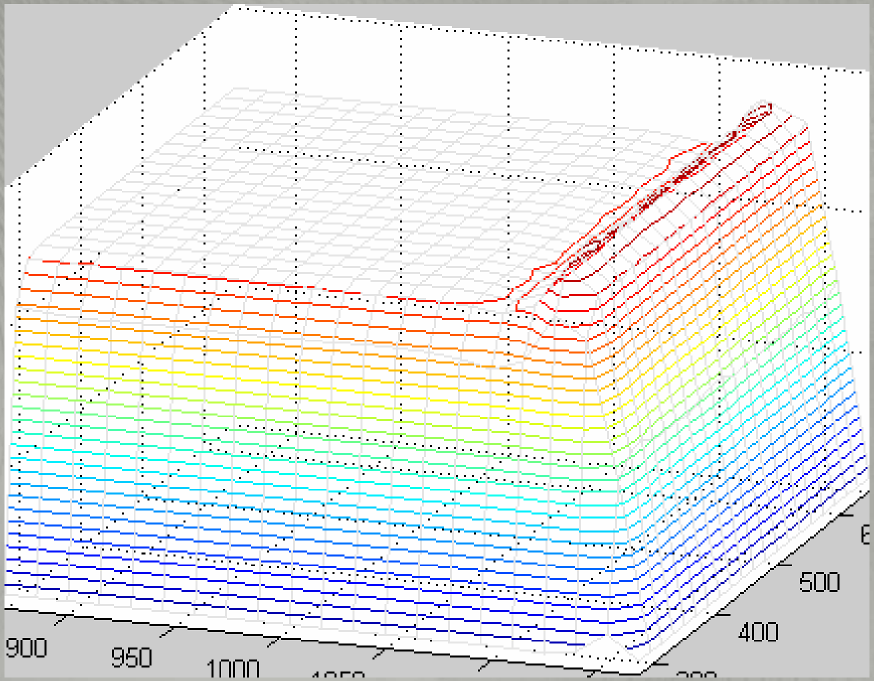
Drying Strains in the Black Cherry Sample



31 % MC   22 %   13 %   5 %

Moisture Profile::Simulation

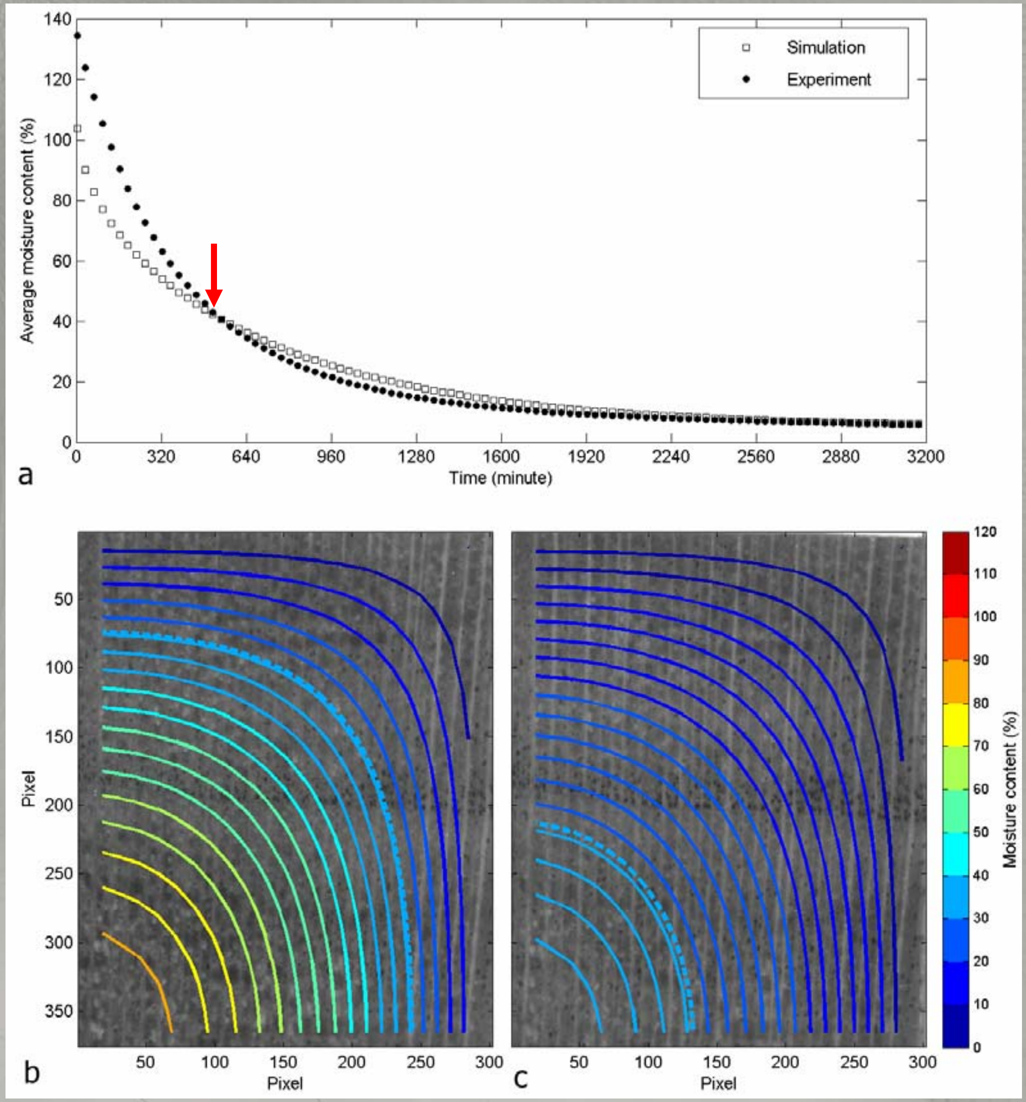
Center of the sample



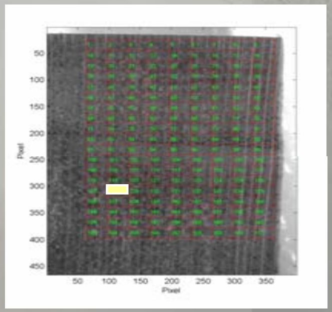
Tangential surface

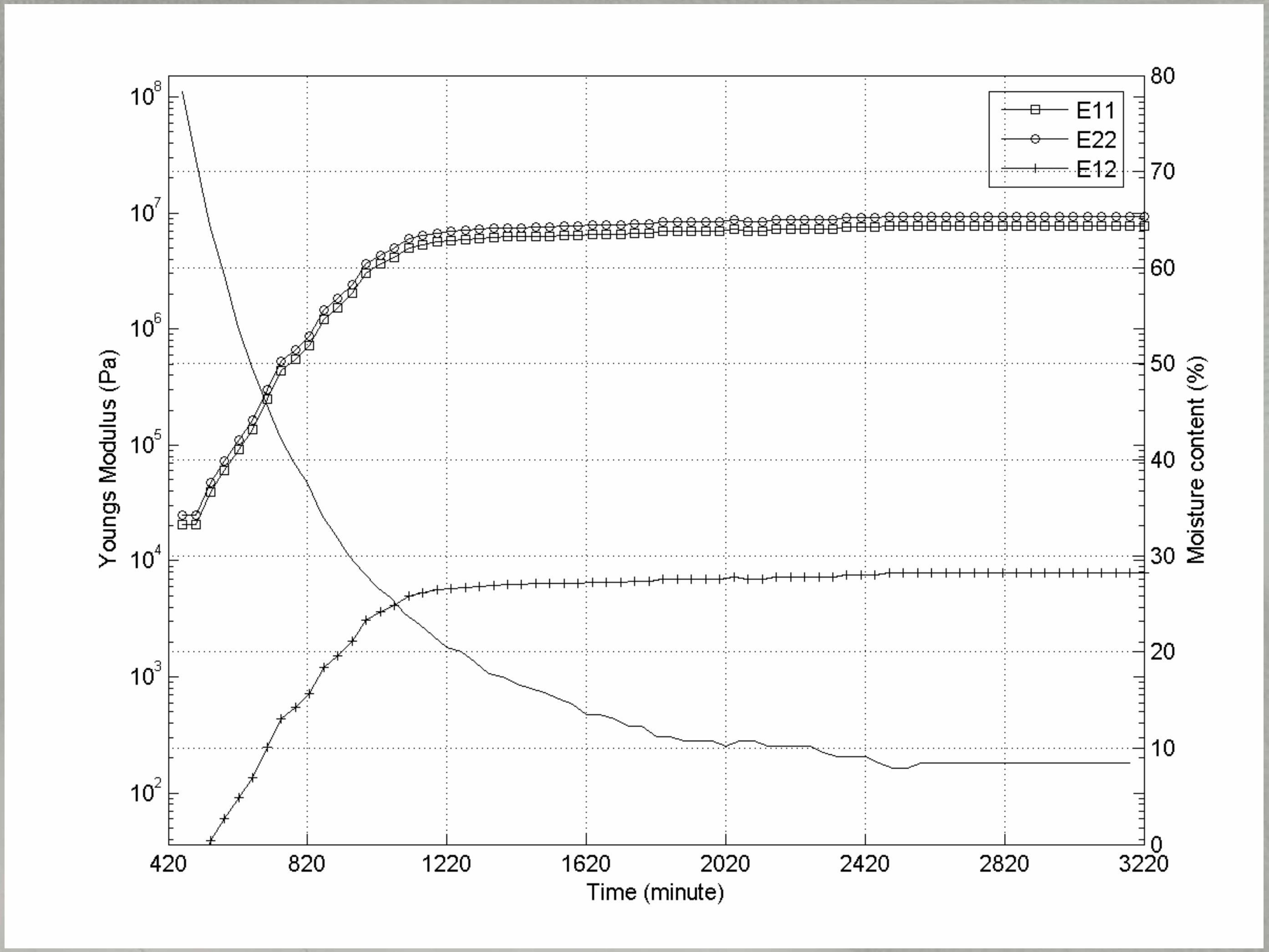
Radial surface

Moisture Profile::Assessment



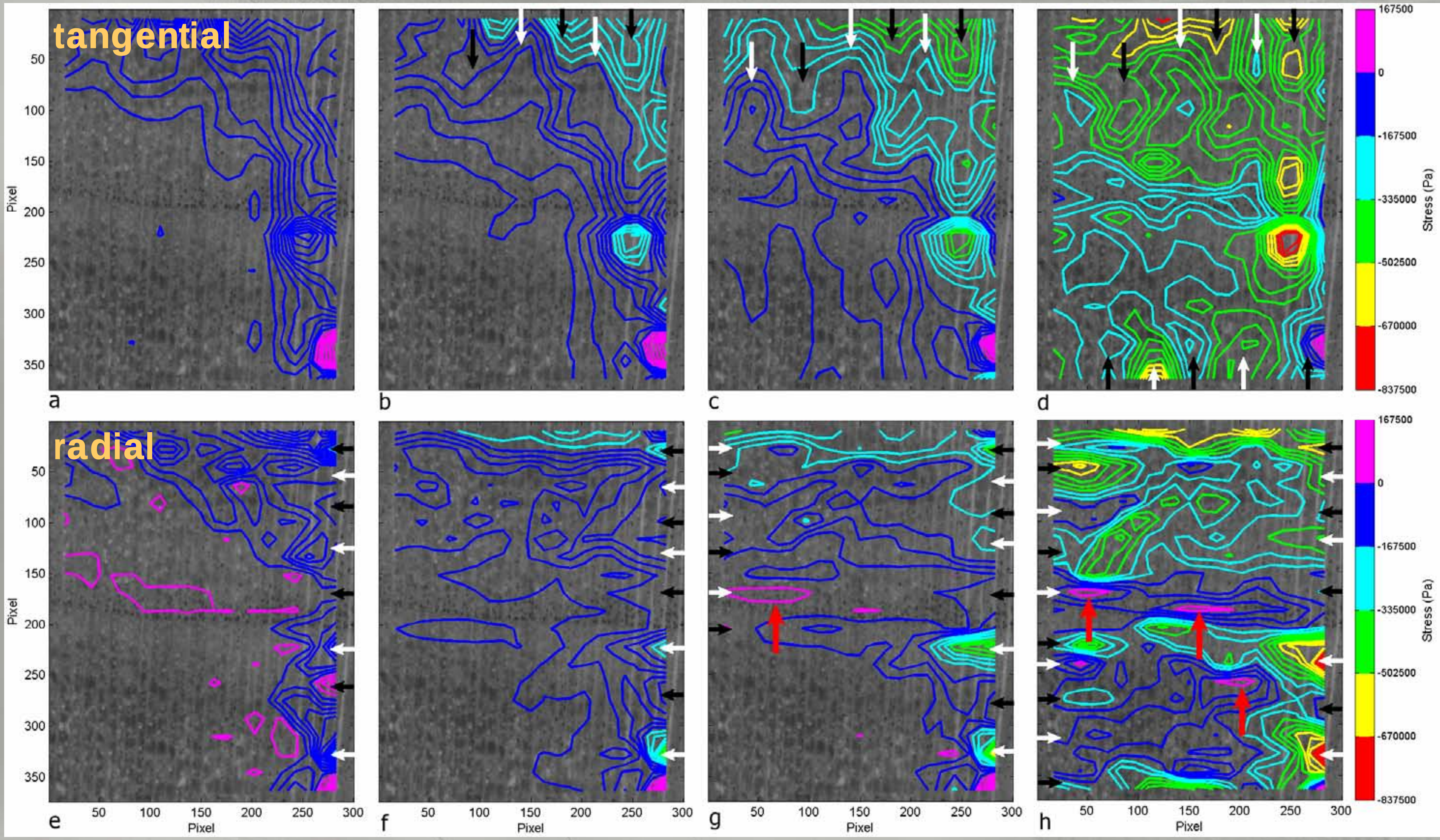
Local Elastic Properties





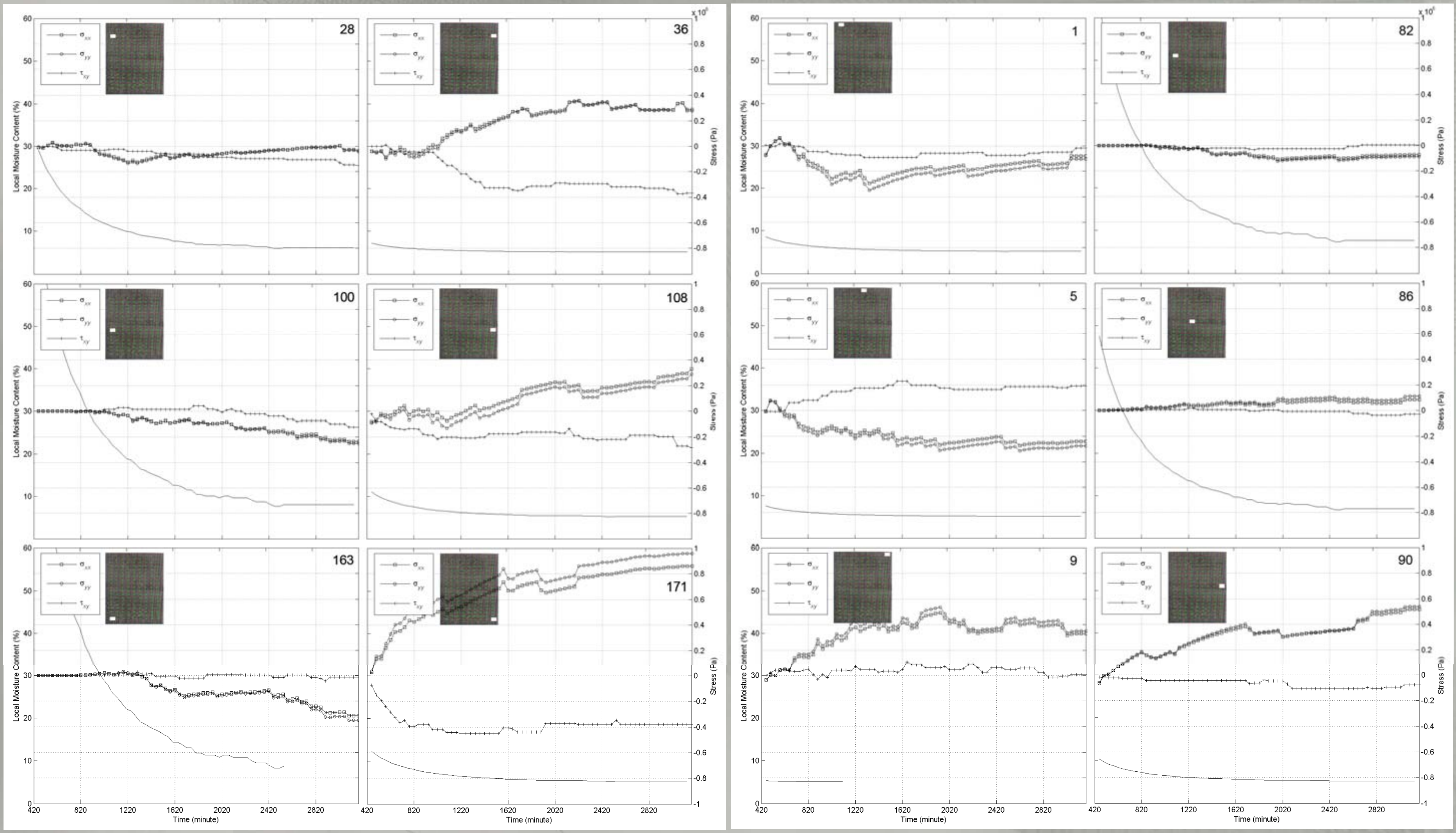
Local region: 128

Drying Stresses in the Black Cherry Sample



31 % MC | 22 % | 13 % | 5 %

Local Drying Stresses



Near the y axis
Near the right surface
Near the top surface
Large vessel regions

Conclusions

- **The EDIC technique and IDEAS were successfully applied to determine drying stresses in wood.**
- **Anatomical structures affect the development of the drying stresses.**
- **Rays generate the alternating pattern of the greater and lesser tangential drying stresses.**
- **Drying stresses were released by positive strain, especially in the radial direction.**