Numerical Modeling of Wood or Other Anisotropic, Heterogeneous, and Irregular Materials

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Hierarchical
Smart
Adaptive
Self-Healing
Multifunctional
Bio
Nanocomposite

(J. Harrington, PhD Thesis)
Morphology-Based Modeling of Structures

- **Material properties**
  - Elastic, viscoelastic, plastic, moisture, temperature, etc.

- **Anisotropy**
  - Longitudinal, radial, and tangential directions (orthotropy)

- **Structure**
  - Polar orthotropic, grain direction, density, cellular structure, knots, etc.

- **Heterogeneity**
  - Earlywood, latewood, fibers, ray cells, heartwood, knots, etc.

Figure 1
How does any model handle M*A*S*H?

- Lower case letter: some attempt, but crude approximation
- Upper case letter: serious attempt, less approximate
- Dash (−): ignores that issue, may mean model is inadequate

Transversely isotropic model

- ma − −
- Transverse isotropy misses low $G_{RT}$

Axial

Fiber Direction

Transverse
- Rectilinear orthotropic model
  - $m_A - -$
  - Ignores actual structure

- Polar orthotropic model
  - $m_A s -$
  - Ignores heterogeneity
Modeling Methods

- **Heterogeneous polar orthotropic model**
  - m A s h
  - Approximate actual structure

- **Realistic heterogeneous polar orthotropic model**
  - m A S h
  - Challenge to include in model
Transverse Compression in Wood

Motivations

- Compression present in structures
- Composite processing
- Wood densification
- Basic science for numerical modeling of cellular materials

Mature Southern Pine

Late Wood

Early Wood

Wood Cells

100 µm

E.V. Kultikova, MS Thesis, VPI (1999)
Experimental Observations

Some References

Key Dependencies
- Anatomical features
  - Softwood
  - Hardwood
  - Earlywood and latewood
  - Ray cells
- Loading direction

Softwood: Douglas Fir
Diffuse Porous Hardwood: Red Alder
FEA of Transverse Compression

- Shiari (2004)
  - Single cell compression
  - Linear elastic, with contact (but difficult)

- Problems with FEA of Realistic Wood Structures
  - Meshing realistic morphology
  - Large deformation/mesh distortion
  - Cell-wall contact

- Why MPM
  - MPM simulation of compaction of foam - Bardenhagen, Brydon, and Guilkey (2005)
  - Easy to discretize complex morphologies
  - Automatically handles contact
Material Point Method Analysis

Loblolly Pine

- Microscopy of wood specimen
- Digitize into BMP file at desired resolution
- Convert pixels to material points
  \[ m - S h \]
- Virtual compression test in desired directions.
- Interpretation of results or analysis of experiments

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Cell Wall: $E = 10.6$ GPa, $\nu = 0.33$, $\rho = 1.5$ g/cm$^3$, elastic-plastic with various yield stresses

Radial loading at 10 m/sec (<0.4% wave speed)
Plastic Deformation
Loblolly Pine - Tangential Loading

Stress (MPa)

0.0 0.1 0.2 0.3 0.4 0.5 0.6
0 100 200 300 400 500 600 700 800 900 1000
100 MPa 500 MPa 2500 MPa

Elastic
Radial
Tangential

Strain

0.0 0.1 0.2 0.3 0.4 0.5 0.6

2500 MPa
500 MPa
100 MPa

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Plastic Deformation
Hardwood Compression

Yellow Poplar

- Mature yellow poplar
  - Diffuse porous hardwood
  - Wider ray cells

- Digitize to MPM model

- Load in radial or tangential directions

- Examine stress state and compare to softwood results

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Yellow Poplar

Radial

Tangential

Stress (MPa)

Strain

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Load Bearing Paths

Radial Loading

Tangential Loading
Transverse Fracture of Wood

Actual Specimen

MPM Model

Defines earlywood and latewood but not radial and tangential directions
Polar Orthotropy

θ = 0°  θ = 90°
Two Images for Structure and Orientation

Input Images

Generated Model

m A S h

<BMP name="../Images/FirSample2.bmp" width="25"
   angles="../Images/FirSample2Angles.bmp">
  <Origin x="0" y="0"/>
  <Intensity mat="1" imin="128" imax="254">
    <Thickness units="mm">1</Thickness>
  </Intensity>
  <Intensity mat="2" imin="0" imax="127">
    <Thickness units="mm">1</Thickness>
  </Intensity>
  <Intensity imin="0" imax="255" minAngle="0.0" maxAngle="90.0"/>
</BMP>
The **CRAMP** Algorithm - **CRA**cks in **MPM**
Sample #4 Results

High contrast, hoop criterion, helped by initial flaw

\[ m A S h \]

No Initial Flaw

Homogenized RT Plane

\[ m A S - \]
Movie from Fred Kamke (OSU), field of view = 30 mm
Compaction Simulations
Anisotropy Complications

- Grain direction changes
- Orientation part of solution
- Anisotropic yielding needed

Red for counter clockwise
Blue for clockwise
Coupled Experiments and Modeling

- Digital Image Correlation (DIC)

[Images of experimental setup and full-field strain field]

Full-Field Strain Field
Simple Tensile Test

Stress $\sigma$

Uniform Strain $\varepsilon$

$E_{xx} = \frac{\sigma}{\varepsilon}$
Simple Tensile Test

Stress $\sigma$

Uniform Strain $\varepsilon$

$E_{xx} = \sigma/\varepsilon$

Nonuniform Strain
Coupling Modeling with Experiments

A. Experiments and Imaging
B. Experimental $\epsilon_{yy}$ by DIC
C. MPM Modeling
D. Angle Mask
E. MPM Calculations

Difference ($\Delta$)

Material Property Input

Adjust Properties

Sensitivity Analysis

Done

Yes

$\Delta$

Prop.

No
Wood Fiber Mat Compaction
Strain Uniformity
Force-Displacement Convergence

Stress (MPa) vs. Time (ms)

-0.30 -0.25 -0.20 -0.15 -0.10 -0.05 0.00 0.05

0.00 0.02 0.04 0.06 0.08 0.10 0.12 0.14

192X192 144X144 32X32

48X48 64X64 160X160

96X96 128X128 144X144

z-direction 772 particles

5 µm spacing

m - S h

10 µm spacing

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Realistic modeling requires attention to

- Material properties
- Anisotropy
- Structure
- Heterogeneity

Simultaneous inclusion of anisotropy and structure is a challenge

- Nearly solved in 2D
- Serious challenge in 3D

Analysis of realistic morphologies has many applications in wood science as well as composites science

Direct coupling of modeling to actual specimens opens up new possibilities
Material Point Method

- MPM useful properties
  - Discretizing realistic structures
    - Requires new work to discretize realistic anisotropy
  - Explicit cracks with crack propagation
  - Handling contact

- You can try it at home
  - Open-source 2D/3D MPM (and matching 2D FEA):
    http://oregonstate.edu/~nairnj/
  - Can Run Calculations and Visualize Results in Graphical Front End
    - Mac Users - complete package available for downloading
    - All Others - java application controls running and visualization (2D only)