Digital Volume Correlation in X-ray Computed Tomography of Wood Composites

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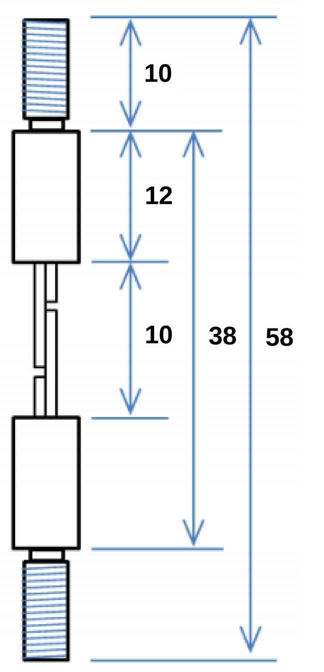
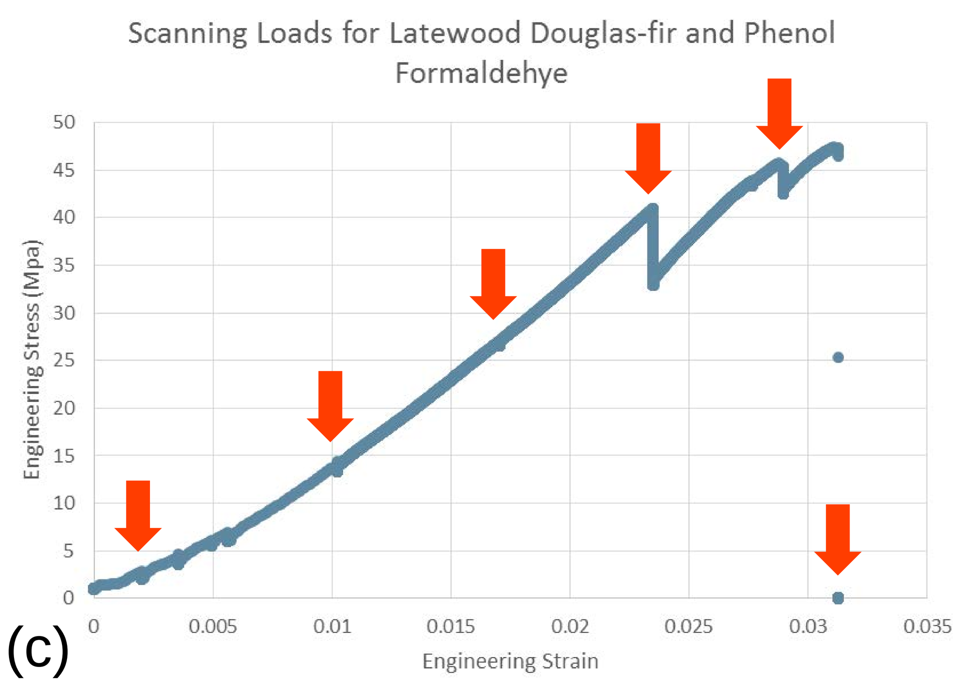
Wood composites are an important renewable building material whose development has recently enabled the expansion of the massive timber construction industry in the US. Products, such as cross laminated timber and laminated veneer lumber depend on strong and durable adhesive bonds. However, the importance of adhesive morphology in bond strength and durability at the wood-adhesive interface is largely unknown. Until recent access to X-ray computed tomography and effective techniques to tag adhesive polymers, non-destructive investigation of adhesive morphology was not possible. An *in situ* stepwise loading and XCT scanning procedure was used to create 3D images of bonded lap-shear specimens - including elastic deformation, plastic deformation and point of failure. By using digital volume correlation (DVC) to track the deformation, adhesive bond morphology will be compared to pre-failure mechanical performance for three wood species and two adhesive types. Wood has an orthotropic structure with uniform features approaching the micron scale, thus presenting a challenge for DVC analysis. To determine the accuracy and precision of DVC in wood tomography, software developed at Oregon State University was applied to compare artificially deformed wood tomography data sets to their applied displacement fields. Based on our tomography data, with resolution 1.3 microns per voxel, we concluded that DVC is a useful tool for measuring micron scale displacements inside wood structures.

(a)



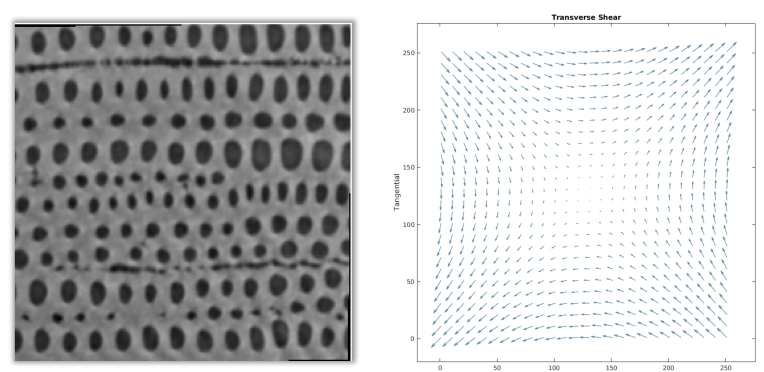
(b) Test specimen geometry. Measurements in millimeters.



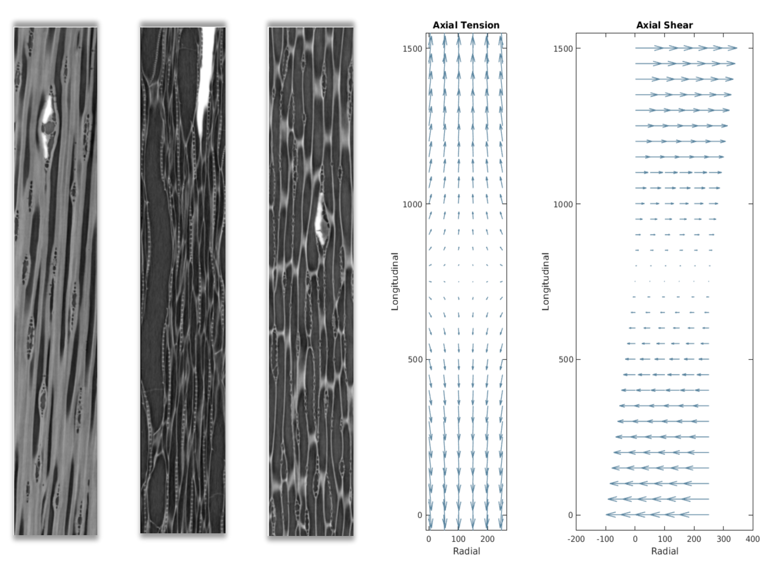
(c)

Step Loading

XCT scans were performed at Advanced Photon Source, Argonne National Laboratory. To capture elastic and plastic deformation of wood adhesive bonds, 109 scans of 22 specimens were performed in a stepwise loading process using a custom mechanical testing device (a). Resolution was 1.3 μm³ per voxel. Lap-shear specimens were approximately 2x2mm in cross-section and 5mm bonded length (b). The experiment was designed for six scans of each specimen, stopping twice in the elastic regime and twice in the plastic regime. The orange arrows above show the scanning positions on an exemplar stress strain curve (c). The sudden drops in the stress are due to stress relaxation in the wood.



(d)

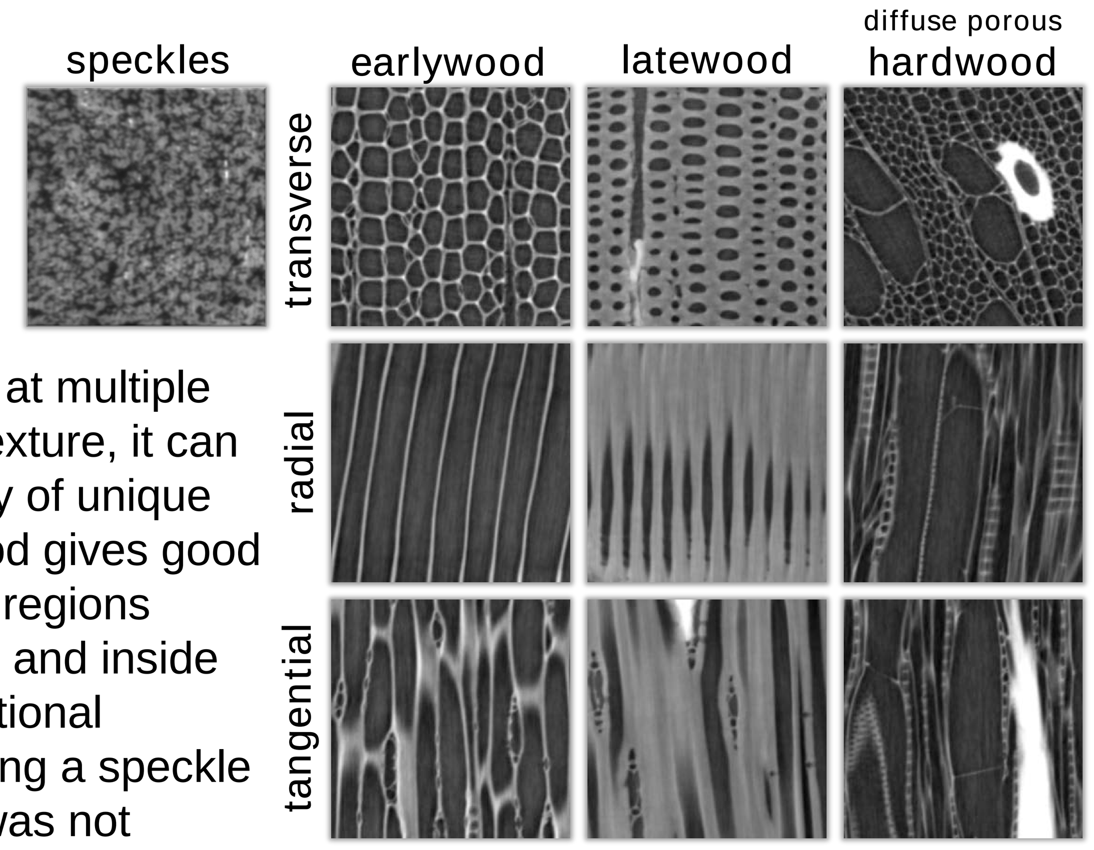


(e)

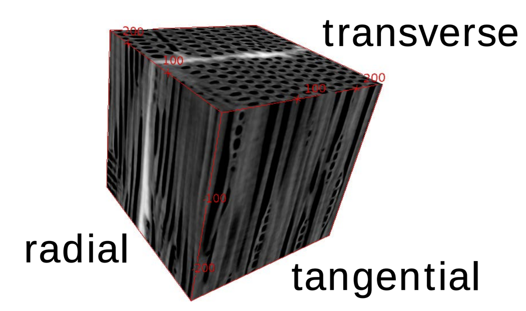
Validation with 4 Modes of Deformation

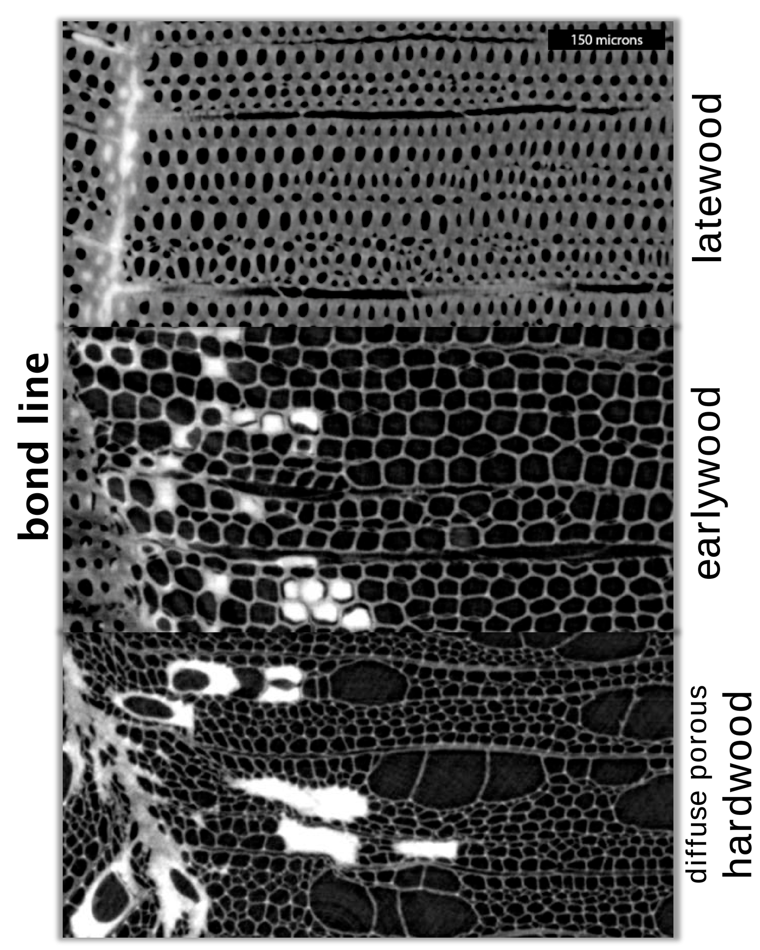
We characterized the accuracy and precision of our DVC software by artificially deforming 256x256x1536p volumes by 1.24% in 4 different modes of deformation: transverse shear (d), axial shear (e), axial tension (e), and uniform translation for each of the three classes of texture in our specimens: earlywood softwood, latewood softwood, and diffuse-porous hardwood. The correlation window size was 40x40x256p. By comparing these applied deformation fields to the deformation fields calculated by our DVC software, quantitative measures of the accuracy and precision of the software were collected. Above are exemplar slices of the wood and the applied displacement fields. Uniform translation is not shown.

No speckles here!

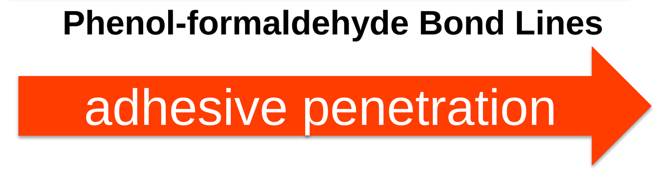


Correlation requires regularly occurring changes in image intensity: texture. The features in the texture need to be smaller than the correlation sub-volume and be unique (or have a unique neighborhood). Because wood is orthotropic, has features at multiple scales, and contains large areas without texture, it can be difficult to correlate. The uniform density of unique cell junctions in the transverse view of wood gives good texture, but the long and wide texture-less regions inside the cell lumens, along the cell walls, and inside vessels, are not good for correlation. Traditional correlation methods involve artificially adding a speckle pattern to improve texture. However, this was not possible for our specimens because we need to use the same datasets for segmentation and adhesive morphology quantification.





Phenol-formaldehyde Bond Lines



Adhesive Morphology and Penetration

The three wood types in our experiment have different structures and densities that cause different penetration depths and morphologies for the adhesive. Additionally, the two adhesives: methylene diphenyl diisocyanate and phenol-formaldehyde, have different flow properties which also influence morphology and penetration depth.

Future Work

Subsets from actually deformed volumes will be correlated to observe the behavior of deformation of adhesive bonds. Mechanical response of bond lines will be compared with quantitative measures of adhesive morphology. Optimal correlation windows for anisotropic texture will be determined. Computed strains will provide input for material point method based models of wood composites.

Acknowledgements

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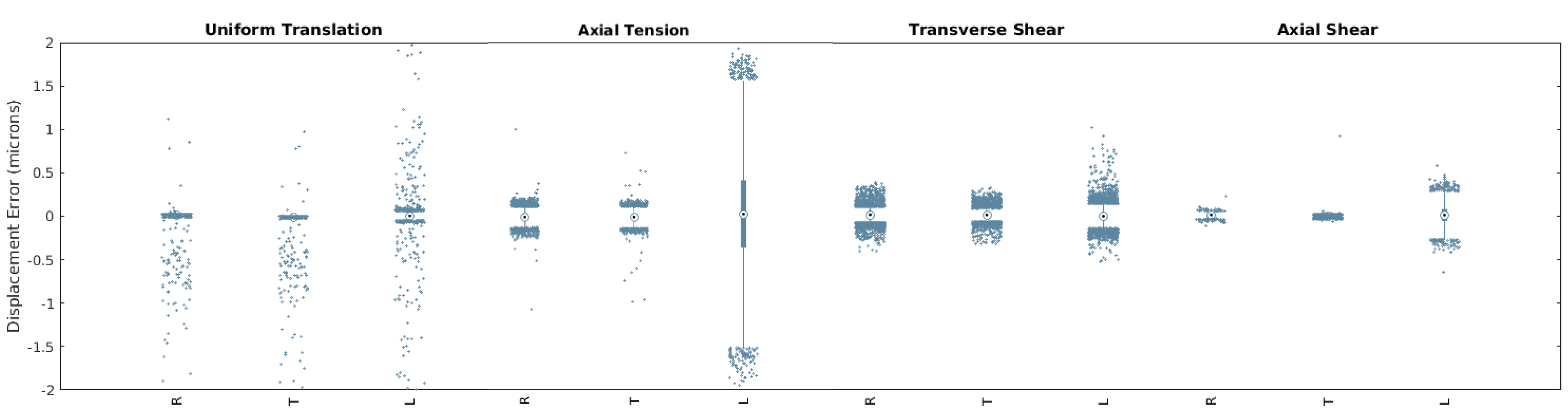
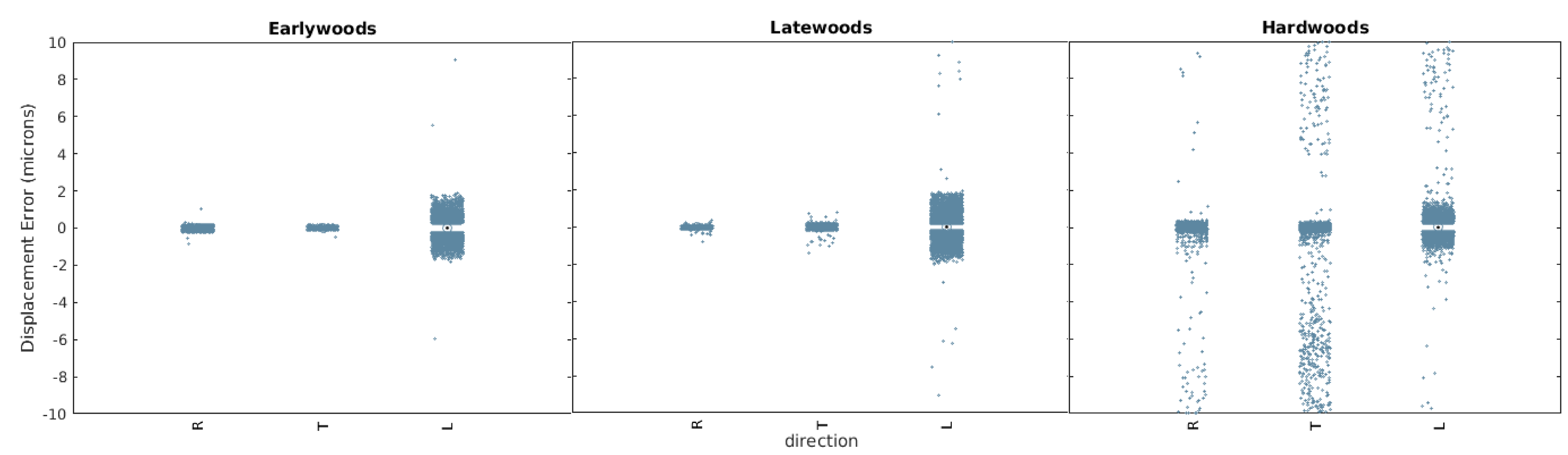


(g) Box plots of DVC displacement error for the radial (R), tangential (T), and longitudinal (L) directions in wood for each of the 4 deformation modes. Each box plot represents 15,000 pairs of correlated points. Outliers are dots at the end of whiskers and represent 1% of points sampled.



(h) Box plots of DVC displacement error for the radial (R), tangential (T), and longitudinal (L) directions in wood for each of the three texture classes. Each box plot represents 22,000 pairs of correlated points. Outliers are dots at the end of whiskers and represent 1% of points sampled.

Quantification of Precision and Accuracy

We used mean displacement error to quantify the accuracy of our digital volume correlation software. While the precision in the radial and tangential directions is consistently less than 0.5 microns, in the longitudinal direction, the precision is often larger than 1 micron (g). The orthotropicity of the precision is not consistent between the three wood textures, hardwood has the widest dispersion of outliers (h). Due to the presence of large untextured regions (vessels), outliers correlate with points 10s of microns away from their correct positions; however, most of these points can be filtered out using correlation function thresholding.