The Application of 3-D X-Ray Tomography with Finite Element Analysis for Engineering Properties of Strand-Based Composites

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ABSTRACT

Strand-based composites are formed by arranging wood strands in a mat and bonding them together with adhesives under heat and pressure. The performance of these products is governed by the properties of wood strands, adhesive, manufacturing strategy, and production process. In this paper, a method of building a model to represent internal structure of oriented strandboard (OSB) based on x-ray tomography analysis and to calculate anisotropic engineering constants of OSB using finite element (FE) technique is presented.

OSB samples from mixed hardwood species were scanned with an x-ray tomography machine and internal structure of the composite was reconstructed into three dimensional images. Internal variations of material density were calculated during image processing, and the voids were identified and reconstructed. The in-plane and out-of-plane distribution of density and voids variations were demonstrated. It was found that the x-ray tomography and image processing technology can be successfully used to obtain density distribution and voids structure in OSB.

A three layer (two face layers and one core layer with different flake alignment levels) finite element model was created to investigate performance of anisotropic wood composite (i.e., OSB). The FE geometry model was based on X-ray tomography images reflecting the actual microstructure of the testing samples. The predicted in-plane moduli showed reasonable agreement with measured data. The study showed that OSB performance can be characterized numerically with FE simulation to achieve the goal of digital testing of the composite material.

Keywords: composites, density, x-ray scanning, voids, wood, finite element

INTRODUCTION

In strand-based wood composites, presence and distribution of macro-voids are generally governed by the random lengths of wood strands and their partial random deposition during the forming process (Suchsland 1962, Dai and Steiner 1994). Although the presence and distribution of macro-voids influence the structural and physical properties of strand-based wood composites, their measurement and quantification are difficult using traditional techniques (Length and Kamke 1996, Ellis et al 1994).

Advanced imaging techniques such as x-ray tomography and magnetic resonance imaging (MRI) have been used to study the structure of granular materials in the last decade. X-ray tomography imaging can distinguish different phases in a material in a non-destructive
manner and has been widely applied to medical science since the 1970s. In recent years, x-ray tomography analysis has also been applied to microstructural characterization of wood and wood products (Chang et al 1989, Sugimori and Lam 1999, Zhang et al 2005), asphalt concrete (Braz 1999, Wang et al 2001), cement concrete (Hall et al 2000), soil (Desruses 1996), and rock (Verhelst 1995). Among the studies for wood-based composites, Sugimori and Lam (1999) successfully measured the size and position of the macro-voids in Parallam using medical x-ray computer tomography (CT) scanning techniques. A database from a series of cross-sectional density distributions in a long specimen was developed. Zhang et al (2005) developed a technique of scanning oriented strandboard (OSB) samples with an x-ray tomography machine and reconstructing the internal structure of the composite into three dimensional images using image processing technology. Internal variations of material density were obtained during image processing, and the voids were identified and reconstructed for various OSB samples. It was found that the x-ray tomography and image processing technology can be used to obtain density distribution and voids structure in OSB. The digital images can be used to generate geometric models used for numerical simulation with finite element (FE) method.

A two-dimensional laminate model predicting engineering constants of OSB including Young’s moduli, shear modulus, Poisson ratio, and linear expansion coefficients was developed and tested (Wu and Lee 2003). In the model, it is assumed that the principal structure unit of OSB is resin-coated wood flakes and the panel is constructed as a set of imaginary flake-adhesive layer stacked up according to the flake orientation distribution. Using the classical lamination theory and wood-adhesive system property, the model predicts well-expected trends of the property change as influenced by flake alignment level and layer structures. To predict the influence of voids on engineering constants of OSB, through-thickness cylindrical voids were combined with a solid strand matrix characterized by the laminate model using finite-element analysis (Wu et al 2004). The model predicts significant influence of an in-bedded void on panel properties. However, the model prediction can be significantly improved with distributed voids of irregular shapes measured directly from the composites. With 3D void structures from CT scanning (Zhang et al 2005), the composite can be modeled as a two-phase material of wood strand matrix and voids. The mechanical properties such as elastic modulus and strength of the system can be then computed using FE methods.

The objective of this study was to build a model to represent internal structure of oriented strandboard (OSB) based on x-ray tomography analysis and to calculate anisotropic engineering constants of OSB using finite element (FE) technique and scanned images.

**MATERIAL AND METHODS**

**X-ray Tomography System**

The x-ray tomography system used in this research is a Model ACTIS 225 System by Bio-Imaging Research Inc. The system consists of x-ray source generator, collimator, sample holder, and detector array. The system uses up to 225kV x-ray source and has up to 10 µm resolution. During scanning, shaped x-ray beams pass through the sample, which is rotated and moved vertically. Due to the different absorption rates caused by density and/or material variations through the sample, the intensities of X-rays passing through the object vary depending on structural difference in the sample. The detector array captures and converts the transmitted x-ray beams into measurable signals. An image intensifier further converts the x-ray energy into light signals which are then digitalized into numerical data by a video camera and turns into images with a computer system. By moving the sample vertically, many slices can be taken through sample thickness, which are then combined through mathematical operations to create three-dimensional CT images.
Wood Composite Sample Preparation

Three-layer OSB was manufactured using mixed hardwood flakes with various combination of furnish quality (i.e., large wood flakes versus fines). Related panel production information is summarized in Table 1. Two replicate OSB samples of 76-mm (length) by 76-mm (width) by 12-mm (thickness) were prepared from each panel group. The samples were conditioned for several months at 25°C and 65% relative humidity prior to x-ray scanning. Sample dimension and weight were measured to determine their volume and mean density. Density distribution through sample thickness was measured with an x-ray based densitometer for all samples.

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>Panel Construction a</th>
<th>Density (g/cm3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S07; S08</td>
<td>Face: 55%WFL; Core: 45%WFL</td>
<td>0.73; 0.70</td>
</tr>
<tr>
<td>S09; S10</td>
<td>Face: 55%WFL; Core: 10%WCM &amp; 35%WFL</td>
<td>0.69; 0.71</td>
</tr>
<tr>
<td>S11; S12</td>
<td>Face: 55%WFL; Core: 20%WCM &amp; 25%WFL</td>
<td>0.75; 0.73</td>
</tr>
<tr>
<td>S13; S14</td>
<td>Face: 55%WFL; Core: 30%WCM &amp; 15%WFL</td>
<td>0.64; 0.62</td>
</tr>
<tr>
<td>S15; S16</td>
<td>Face: 55%WFL; Core: 45%WCM</td>
<td>0.71; 0.69</td>
</tr>
</tbody>
</table>

a WFL – Wood face large (flake); and WCM – Wood core material.

X-Ray Scanning and Image Analysis

X-ray imaging of the OSB samples was done with 140 kV x-ray source. The system was calibrated according to material properties and the size of the sample. It includes offset, gain, horizontal wire, vertical wire, central ray, and wedge calibration. This process is very important for obtaining good images in the scanning process. Due to low density of wood-based materials like OSB, lower x-ray source was used in the scanning. Eight slices were scanned in one rotation and the slice increment was about 0.5 mm. The average value of eight shots at one position was used for image reconstruction and analysis. For each sample, 24 slices was taken along the thickness direction with each slice representing about 0.5 mm thick of internal structure. The image set from each sample was used to create three dimensional visualization of its internal structure. The gray images obtained were first processed by removing the border of each slice, which is the area between reconstruction area and actual sample area. The reconstruction was carried out using ImagePro, IDL and Voxel program package [Zhang et al 2005]. The IDL program allows making section or block view from the reconstructed three dimensional images. It also has other options to make the three dimensional visualization more vivid and colorful. Several computer source codes based on this software language (IDL) were written to carry out three dimensional reconstructions for void quantification.

Voids Identification and Quantification

In the binary image, voids and wood flakes were assigned with different digital values according to the computerized x-ray energy density obtained from scanning process. Voids were identified from the structure by setting a proper threshold in binarized images. The total area assigned as voids were then calculated and the voids ratio was quantified using these image tools. The threshold value selection plays a critical role for this process. However, only the boundary pixels of voids are sensitive to the threshold adopted in the quantification. The number of such boundary pixels depends on the size and shape of the voids. The ratio between total boundary pixel and total voids area influences the accuracy of the voids quantification. This may explain some variations observed in samples with different core size, which generate different size of voids. To reduce this influence, total pixel values of scanned images were used and related to measured local material density.
The voids ratio distribution along the panel thickness was obtained from every slice. By measuring the void ratio for divided areas on each image slice, void distribution along the width and length directions were created. Macros were made to carry out this calculation in image processing software package ImagePro and IDL, which can make contour plots of the pixel value. The total void ratio for a sample was then statistically summarized. Based on the binarized image, three dimensional void structure of samples was created for visualization and characterization using the IDL program. In this process, only void data of each slice was filtered out and used to create the three dimensional visualization. From these three dimensional images, general void ratio magnitude can be visually characterized.

**Finite Element Model**

Three-layer OSB with different flake orientation and flake quality for face and core layers was considered in the modeling. Each sample was x-rayed to obtain 20 cross-section images through sample thickness as described above. The layer division for each sample includes 5 slices for each of the two face layers and 10 slices for the core layer. From the analysis, pixel-value map for each layer was obtained. The correlation between layer mean material density and pixel value was obtained for each sample. A four layer model panel was formed by combining the outer five slices from each surface to form two face layers and combining and dividing the inner 10 slices to form two core layers with five slices for each layer. The pixel-value map for each layer in the four-layer model panel was generated by combining measured pixel values at each corresponding position of individual slices forming the layer. A total of 2500 discrete pixel values were generated from the layer pixel-value map to represent the layer. Local material density corresponding to each pixel value was predicted using the pixel value–density correlation. In-plane elemental elastic constants were generated using regression models describing relationships among panel property, density, and fines content for the layer (Han and Wu 2006). The out-of-plane elemental material constants were estimated based on published literature for strand composites.

A model with totally 10,000 elements for the four layers was created to simulate each quarter of the testing sample (Figure 1). A 3D 8-node solid element was used in the modeling. Pixel variation for each layer of the panel was generated with IDL programming, which can be read by a FORTRAN program. The program was written to automatically import the information of pixel value variation and to calculate elemental elastic moduli based on pixel-
density correlation and density-elastic modulus relationship obtained from previous studies. The program was also used to generate ABAQUS input file and output request based on intended test simulations. Considering the variation of material properties due to considerable material density variation in OSB, each element was assigned a set of material constants according to the local density obtained from image processing. Orthotropic material properties were considered in the simulation. The loading and boundary conditions were set to be the same as real test conditions of uni-axial tensile test. The predicted strain and applied stress along each of the two in-plane directions (i.e., 1 and 2) were used to calculate overall in-plane moduli for each sample.

RESULTS AND DISCUSSION

Measured Void Distribution
Typical gray images from x-ray scanning are shown in Fig. 2 for sample S15. The images provide visualization of a section cut along sample thickness. Voids (dark color) are randomly distributed across the plane as shown. There was a significant mix of large and small flakes and flake boundaries are clearly seen from the section images. The core layer (Figure 2b) had more small strands and lower density, leading to more voids compared to the face layer (Figure 2a). Three-dimensional panel reconstruction was done using colored image slices with software package ImagePro and IDL for the given panels (Zhang et al 2005).

![Figure 2. Typical gray images from panel surface (a) and core (b) using X-ray scanning with slice thickness of 0.5 mm (sample S15).](image)

The void area and perimeter were measured using ImagePro and IDL for each slice for a given sample. The obtained void ratio distribution along the panel thickness with a threshold value of 100 is shown in Figure 3 (a) for the selected samples. It can be seen that measured void ratios varied from sample to sample. The void value was high in panel center and decreased toward panel surface, which agrees well with density variation along OSB thickness. Figure 3 (b) shows the correlations between measured void ratio and layer density across the panel thickness (sample S09) at various threshold levels. Over a large density range, voids in OSB decreased exponentially with increase in density. At high density levels, compression of wood itself under heat and pressure led to little change in the between-strand voids. At the low density levels, the voids increased rapidly as density was reduced.

The void ratios obtained from image processing depend on the selection of threshold value used (Figure 3b). At a given density level, measured void ratios increased with increase of
the threshold value. Thus, for randomly distributed voids like these in OSB, defining the void boundary through properly thresholding the images had a large influence on actual void value obtained. For all OSB samples, general distribution trend of voids was the same. In order to eliminate the effect of the threshold value selection, the total pixel value, which is related to image density intensity, was related to the measured layer density for each sample.

Figure 3. Void ratio distribution across panel thickness for selected samples at threshold value =100 (a); and void ratio – mean density correlation along panel thickness at different threshold levels (Sample S09 - b).

Figure 4 shows typical plots between layer density and total pixel values (Sample 09 and Sample S15). Sample density is linearly related to the pixel value for all samples. The relationship can be used to predict OSB density variation based on measured pixel values for a given panel type.

Figure 4. Correlations between measured density and total pixel value from CT scanning (Left- Sample S09 and Right - Sample S15). Lines show regression fit.

Predicted Density and Modulus Distribution
Figure 5 shows typical contour plots of measured in-plane pixel value, predicted density, and moduli (face layer from sample S15). The predicted density distribution was obtained using density-pixel value relationship established for each sample (e.g., Figure 4). Modulus properties (i.e., E1 and E2) were generated using regression models describing relationships among panel property, density, and fines content for the layer (Han and Wu 2006). The ranges for pixel value, density, and moduli are, respectively, 0 to 255, 0 to 1000 kg/m$^3$, and 0 to 30 GPA. However, in order to make the contour plots easy to read, the contoured lines
were chosen at the medium values. For pixel value, 100, 150 and 200 were used. For
density map, 600, 800, and 1000 kg/m³ were used. For material constants, E1 and E2, 5, 10
and 15 were used based on the mean value of about 10 GPA in the measurement.
Significant variability in pixel value (Figure 5a), density (Figure 5b), and moduli E1 and E2
(Figures 5c and 5d) existed in OSB as shown.

From the pixel value map, it can be seen that the pixel values distributed more uniformly in
surface layer than these in core layer; and generally pixel value in surface layer was larger
than that in core layer. The pixel-value variation pattern is also different among different
samples. This could be due to the difference of small wood particles used in various panels.
In general, face layer had larger modulus values compared to the core layer. The modulus
distribution was also more uniform in the face layer for a given panel.

**Figure 5.** Contour plots of measured in-plane pixel value (a), predicted density (b), modulus E1 (c) and modulus E2 (d) distributions (face layer from sample S15).
Deformed Shape and Predicted Stress Distributions
Figure 6a shows a typical deformed sample shape after stressing under uni-axial tensile loading. With applied stress along the 1-direction, panel edges along the 2-direction distorted differently due to in-plane density and material property variations. From the deformation data, overall Poisson’s ratio of the panel can be calculated. Typical stress contours from the simulation results were plotted (Figure 6 for sample 15). For the tension test along axis 1 (i.e., parallel to the face strand alignment direction), the stresses in face layer were considerably larger than these in the core layer due to the different stiffness values of these two layers. There was a significant variation in the predicted out-of-plane stresses (S33) within the plane of a given panel.

Predicted Panel In-plane Moduli
The predicted strain and applied stress along the two in-plane directions (i.e., 1 and 2) were used to calculate in-plane moduli for each sample and the results were compared with measured data (i.e., static bending moduli – Han and Wu 2006). As shown in Figure 7, the FE model prediction shows a general agreement with measured data for various test samples, given the large structural and property variability of OSB products. In general, E1 shows a better agreement between predicted and measured data, and E2 has more variability among various panels. The accuracy of the FE prediction depends on many
variables including generation of actual internal void structure information and estimation of orthotropic elemental material constants.

![Graph](image-url)

**Figure. 7**. A comparison of overall panel property (i.e., in-plane elastic moduli) from prediction and measurement for various OSB samples.

### CONCLUSIONS

The presence and distribution of macro-voids in strand composites significantly influence their structural and physical performance. An attempt was made in this study to generate internal void structure of OSB using CT technique and to model the engineering properties of OSB using finite element method and scanned images. From the study, it can be concluded that X-ray scanning technology enables internal structure visualization and characterization of strand composite material. The developed image processing technology enables phase identification and quantification (such as voids) in the composite panel. In-plane density distribution can be obtained from image analysis through density – pixel value correlations. This technique shows potential in other material with material density and orientation variance. The finite element analysis shows that the performance of anisotropic structural wood composite (i.e., OSB) was strongly related to the pattern of variations of material structure and properties. The developed methodology combining x-ray tomography with FE analysis has potential to achieve long-term goal of digital testing of wood composite materials. Future publications will present information on composite strength, failure mechanisms, and strand-void interfaces as influenced by strand quality and panel processing variables.

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### REFERENCES


