Materials Teasting Research

Evaluating the Effect of Inner Layer Grain Orientation on Dimensional Stability in Hybrid Species Cross- and Diagonal-Cross-laminated Timber (DCLT)

Shaghayegh Kurzinski[1], Paul Crovella[2], & William Smith[2]

Wood deformation due to moisture adsorption and desorption in the cell wall components challenges the dimensional stability of multi-layer wood-based panels. This is a common issue in timber products with single board products and parallel glued layers (such as Glued-laminated Timber; GLT). Orienting the inner layers of timber products at an angle, like plywood and Cross-laminated Timber (CLT), with the perpendicular (90°) orientation of the inner layers, helps minimize overall shrinkage and swelling of the composite panel. However, due to the perpendicular orientation of the layers, Cross-laminated Timber (CLT) exhibits a lower out-of-plane bending stiffness than a parallel-layered Glued-laminated Timber (GLT) panel. An optimized modified orientation of the inner layers in a diagonal direction could improve dimensional stability compared to GLT while developing a better structural performance than CLT. The present study evaluates the dimensional stability of small specimens of four-layer Diagonal-Cross-laminated Timber (DCLT) with a hybrid layup consisting of a high-density hardwood species, black locust, in the top and bottom layers, and a low-density softwood species, eastern white pine, in the asymmetric inner layers. The results indicate that increasing the inner layer fiber orientation angle improves the dimensional stability of the panels. While the dimensional change in the length of the panel (longitudinal) is negligible, by varying the inner layer angle-ply from 0° to 90°, the percentage changes in width (tangential), thickness (radial), and volume reduced respectively from 3% to 0.8%, 1.6% to 0.4% and 5.1% to 1.3%. Since the dimensional tolerances of the CLT due to the moisture content in the manufacturing process and the in-service conditions have already been established in the design and building standards, the result of this study can be helpful for the construction industry to predict the potential dimensional change (%) and corresponding required tolerances for DCLT panels when used in building structures.

Keywords: *Dimensional stability, Moisture Content, Cross-laminated Timber (CLT), Diagonal-Cross-laminated Timber (DCLT), Grain Orientation*

1 Introdcution

Wood is a hygroscopic material which means its moisture content (MC%) varies with the temperature and relative humidity (RH) of its surroundings [1]. A wood product will adsorb and desorb moisture from the surrounding air until it reaches equilibrium moisture content (EMC). EMC is defined as a balance point between the MC% of wood and that of the surrounding environment [2]. The accompanying change in the size of wood is referred to as dimensional stability and will affect how a timber product will move and distort in service. As illustrated in Figure 1, wood is composed of a porous microstructure with pits, and pathways through cell walls connecting the lumina to adjacent cell walls made from cellulose, hemicelluloses, and lignin. Moisture changes in these components can lead to wood deformations such as shrinkage and swelling and to issues for both the serviceability and the load-bearing capacity of the timber structure. In a dry atmosphere, the wet (green) wood loses moisture in the form of water vapor since the solid cell walls of wood are virtually non-porous. Therefore, water molecules leave the cell walls resulting in a decrease in the dimensions of the cell wall material (shrinkage). Similarly, water molecules entering the cell walls cause the dimensions to increase or swell [3].

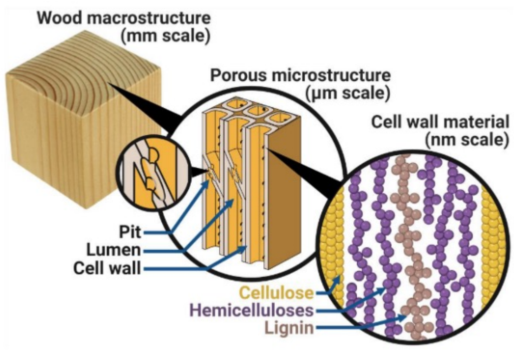

Figure 1. Simplified Overview of Wood Structure on Different Length Scales. Image Courtesy: Thybring et al. [3]

Wood is also an anisotropic material meaning that its properties differ according to the direction of the grain (radial, tangential, longitudinal). Due to the cellular structure of wood, the dimensional deformation is greatest in the tangential direction of the annual growth rings. The moisture-induced radial dimensional change is approximately one-half that of the tangential change. However,

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the longitudinal shrinkage or swelling is negligible (between 0.1% and 0.2% per 1% of the green dimension) for most uses, and it is not considered when the effects of dimensional change are analyzed in wood building design [4].

To ensure efficient material utilization and address the inherent variability of wood products, engineered mass timber products have been developed [5]. Mass Timber products are the newest technology in Engineered Wood Products (EWP). Due to their load-carrying capacity and the possibility of prefabrication, the two most favorable mass timber products are Glued-laminated Timber (GLT) with all layers glued parallel together, and Cross-laminated Timber (CLT) with layers glued in transverse and longitudinal directions. One common issue with mass timber products is the dimensional changes for products with parallel glued layers (such as GLT) due to changes in wood moisture. Since CLT is alternately laminated in the longitudinal and transverse directions, its dimensional changes due to moisture changes, are smaller compared to other mass timber products [6] as each layer of glued timber physically constrains and minimizes dimensional change of the adjacent layer at right angles to it. To overcome the dimensional stability challenges of the mass timber products, while maintaining relatively improved rolling-shear structural performance, a modified orientation of the inner layers in a diagonal direction can be used. As shown in Figure 2, Diagonal-Cross-laminated Timber (DCLT; [7]) is a composite timber product, consisting of inner layers which are rotated at different angle-ply orientations between 0 and 90 degrees to the outer layers.

2. Material and Methodology

2.1. Specimens Preparation

The specimens were fabricated with a hybrid layup consisting of high-density hardwood species, black locust in the top and bottom layers, and low-density softwood species, eastern white pine in the inner two (±α) layers. The black locust boards in this study were purchased as rough-sawn, random width 31-mm thickness, and 3-m length from a sawmill in Newfield, NY. The eastern white pine boards were purchased as NeLMA finish grade, flat-sawn with 22-mm thickness, 197-mm width, and 3.65-m length from a local lumber yard in Syracuse, NY. The eastern white pine boards had been kiln-dried and planed, but the black locust boards needed to be dried and planed before fabrication. These boards were placed in an environmentally controlled room to dry to an equilibrium moisture content of approximately 12%. They were then surfaced and planed to the desired thickness of 19-mm, and the white pine boards were cut to appropriate angles using a miter saw. The processed pieces were then face-glued with 1C-PUR adhesive (Loctite HB X452 Purbond, Henkel Corporation, Bridgewater, NJ) with a recommended spread rate of 180 g/m^2 to glue the top and bottom of the lamina under clamping pressure. This clamping pressure was controlled- by calibrated tightening torque to attain a minimum pressure of 410 kPa (60 psi) for 24 hours, using a mechanical press. The 1C-PUR (PURBOND® HB X452) is a single-component adhesive system that cures with moisture, and its only difference from HBS

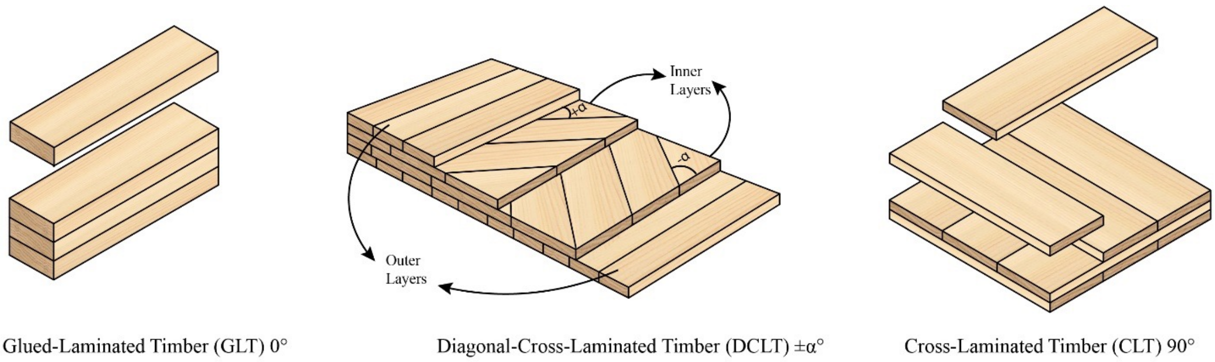

Figure 2. GLT, DCLT, and CLT Lay-up Configurations

This article presents results of the effect of grain orientation on dimensional stability by evaluating the tangential, radial, and volumetric changes of small DCLT samples with grain orientations of ±10°, ±20°, ±40°, ±70°, and small samples of GLT (0°) and CLT (90°). Also, to provide improved structural performance, these small specimens are made of a hybrid species layup consisting of a hardwood species in the outer layers (Figure 2), and a softwood species in the inner layers (Figure 2). The dimensional changes of the samples have been recorded based on an 8% change in moisture content in an environmental chamber, and the results of the DCLT specimens have been compared with the GLT and CLT samples to show the effect of grain orientation of the inner layers with an angle between 0 and 90 degrees.

adhesive (more commonly used for CLT fabrication) lies in fire performance, which is not a point of interest in this research. However, this adhesive was used successfully without any specific primer and was a resource available in the research laboratory [8].

The final large-scale specimens were four-ply 76 mm (3 inches) thick, 305 mm (12 inches) wide, and 2.74 m (108 inches) long panels, with two asymmetric white pine inner layers angle-ply oriented at 0° (GLT), ±10°, ±20°, ±40°, ±70°, and 90° (CLT) and parallel black locust outer layers. These large panels were tested in bending during a separate research study [9] and the small specimens utilized in this swelling study were cut from minimally stressed ends of these large-scale panels after the bending stiffness tests.

The average moisture content of the large-scale boards was measured as 11.8% at the time of fabricating the large-scale panels, however, these panels were left in an approximately 22° C (72° F) temperature and 40% RH laboratory environment for several months before being cut to the small specimens for this study.

In addition to the GLT/DCLT/CLT specimens, three small clear straight-grained replicas of black locust and three replicas of eastern white pine with true longitudinal, tangential, and radial surfaces were cut to provide the shrinkage/swelling dimensional changes comparison between the hardwood and softwood species used in the study. The final sample size included a total of 12 specimens, two replications of each angle-ply orientation (DCLT 0° (GLT), DCLT ± 10°, DCLT ± 20°, DCLT ± 40°, DCLT ± 70°, DCLT 90° (CLT)), and six small clear black locust and eastern white pine specimens (three replications of each species).

2.3.Moisture-Induced Swelling Test

The specimens were placed in a 0.85 m^3 (30-ft^3) PGC (Parameter Generation and Control, Black Mountain, NC.) Temperature and Humidity-Control Chamber set at 24˚C temperature and 90% RH. Specimen weights were monitored daily until equilibrium was reached after 35 days. The final MC% was measured by placing one of the samples in the oven to dry and using the weight data of this sample, according to Equation 1. The specimens' outside maximum dimensions were recorded using a digital caliper with 152.4 mm (6 inches) long jaws sufficient to cover both species of hybrid layers and these readings were compared with their initial dimensions. The dimensional change (swelling/shrinkage) of each specimen was acquired according to Equation 2.

Figure 3. Representatives of DCLT Sample Cut to Random Sizes

2.2. Measurement of Initial Moisture Content by Oven Dry Method

The most accurate method to measure the MC% of wood is the oven-dry method. Individual specimens of wood to be tested are weighed (green weight) on a balance and placed in a ventilated oven set at just above the boiling point of water, 103± 2°C (219°F). Samples are kept in the oven until they reach a constant weight, which usually takes 24 to 48 hours for samples of this size. The new weight is called oven-dry weight and is then used to calculate MC% in the sample. MC% calculated in this way could be over 100% because the denominator in the equation is the dry weight, not the total weight. Regarding this method, the initial dimensions, weights, and moisture content (MC%) of the specimens in this study were recorded using Equation 1 and by placing a similar sample in the oven set at 100°C.

$$MC\ \% = \frac{W_g - W_o}{W_o} \times 100$$

Equation 1: Where W_g is the green weight of the wood and W_o is the oven-dry weight of the wood.

$$Swelling\ \% = \left(\frac{D_{at\ final\ MC\%} - D_{at\ initial\ MC\%}}{D_{at\ initial\ MC\%}}\right) \times 100$$

Equation 2: Where D = *Longitudinal or Tangential* dimension (as the radial dimensional change is negligible)

Finally, a comparison was made between the swelling/shrinkage dimensional changes of the specimens relative to the angle-ply orientation of the inner layer.

Also, the dimensional changes for the two species used in this study; eastern white pine and black locust, can be theoretically predicted using the change of MC% of the green to oven-dry provided in the USDA Wood Handbook [10] and Equation 3 to be compared by the measured dimensional change from the moisture-induced test of this study.

$$Swelling\ \% = S_0 \times \left(1 - \frac{x}{MC_{fs}}\right) \times 100$$

Equation 3: Where S_0 is the percent shrinkage from the green condition to oven-dry, x is the new and final MC%, and MC_{fs} is the fiber saturation point, and here is assumed to be 30% MC% as an approximation.

3. Results and Discussion:

The final dimensions of each specimen were compared with their initial dimensions before being placed in the environmental chamber. The initial moisture content of the small samples of this study was recorded at approximately 7% before being placed in the environmental chamber and after moisture equilibrium, they reached 15% moisture content. This means their total dimensional changes account for an 8% total MC% change. As shown in Figure 4, the most dimensional changes in three directions belong to GLT and DCLT±10 samples. Between all specimens, the greatest dimensional change occurred in the tangential direction followed by radial and longitudinal directions. The results indicate that by increasing the angle of fiber orientation of the cross layers, the dimensional changes decrease. Therefore, the dimensional stability increases by changing the cross-layers fiber orientation from 0° to 90° and CLT is the most dimensionally stable panel among all samples.

Since CLT has been used in the industry for more than two decades, the dimensional tolerances for both manufacturing the panel and, in service, due to the moisture changes, have been established in the building and design standards. For instance, APA/ANSI PRG 320 -2019: Standard for Performance-Rated Cross-Laminated Timber [11], states a change of 0.4%-0.5% in the thickness direction of the (generic, standard and non-hybrid) CLT panel associated with a potential 2% moisture content change in the service. Therefore, the potential dimensional tolerances of the DCLT panels with ±α angle-ply inner layers can be predicted when measured as a coefficient of the CLT dimensional changes as shown in Table 1.

The final predicted values for the individual species of the DCLT specimens are reported in Table 1 based on the USDA Wood Handbook [10]. The experimental results of dimensional changes from six small clear specimens of black locust and eastern white pine are presented in Table 2. As shown, black locust hardwood specimens indicate a higher dimensional change (swelling) due to moisture change compared to softwood eastern white pine specimens. These measured dimensional changes (%) for both species are in agreement with the published swelling/shrinkage percentages (for 8% MC% change) in the USDA Wood Handbook (Table 2) [10].

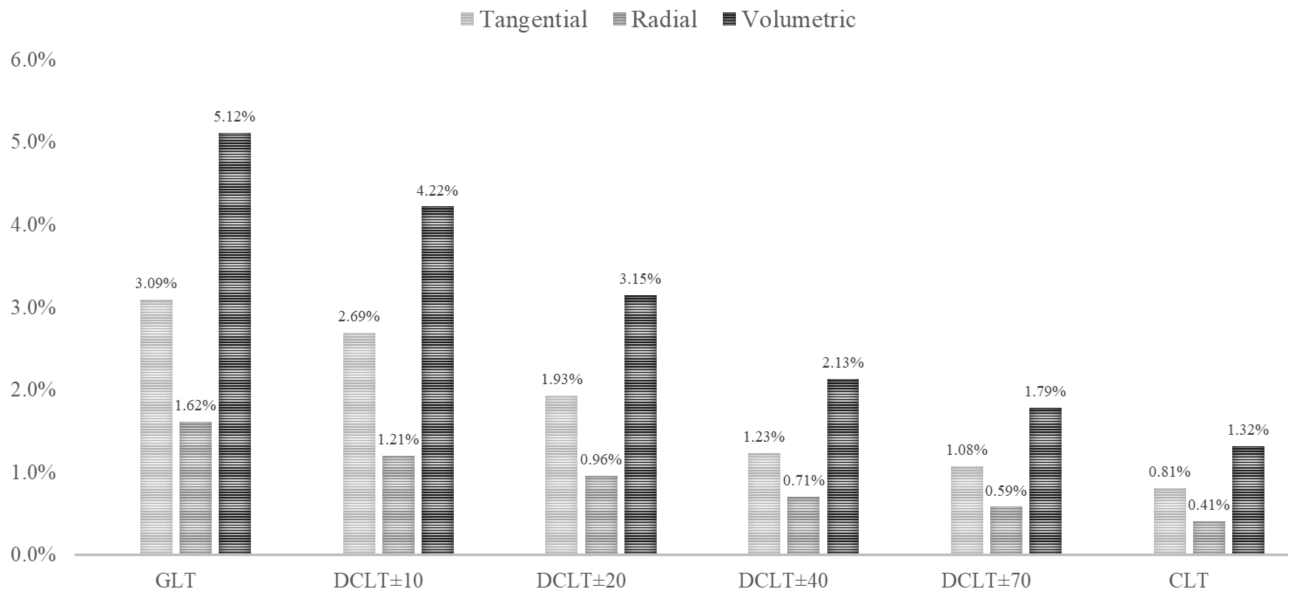

Figure 4. Dimensional Changes Due to 8% Moisture Change in the Hybrid-Species DCLT Panels

Table 1. Corresponding Coefficients of DCLT Panels' Dimensional Changes to CLT Dimensional Changes

Specimens	Coefficient to CLT Dimensional Change%	
	Thickness	Width
GLT	3.9	3.8
DCLT±10°	2.9	3.3
DCLT±20°	2.3	2.3
DCLT±40°	1.7	1.5
DCLT±70°	1.4	1.3

Table 2. Predicted and Measured Dimensional Changes Values from USDA Wood Handbook and Moisture-Induced Test

Species	Dimensional Change %			
	Method	Radial	Tangential	Volumetric
Eastern white pine	USDA Handbook	1.11	3.25	4.37
	Moisture-Induced Test	1.90	2.30	4.40
Black locust	USDA Handbook	2.45	3.84	5.43
	Moisture-Induced Test	2.50	3.00	5.50

4. Conclusions:

The present study has investigated the dimensional changes due to moisture change in hybrid species four-ply DCLT panels

and compared the results concerning the grain orientation to the dimensional changes in CLT and GLT panels with the same layup. The results show that increasing the angle of the cross-layers' fiber orientations from 0° to 90° can improve the dimensional stability mostly in the tangential direction. While the tangential dimensional changes are small and the radial and longitudinal ones might be negligible, CLT has been confirmed to have the most dimensionally stable orientations compared to the angled DCLT panels. Since the dimensional tolerances of the CLT due to the moisture changes in the manufacturing process and the service have already been established in the design and building standards, the result of this study can be helpful for the construction industry to predict the potential dimensional change (%) and corresponding required tolerances for the DCLT panels when they are expected to be used in the building structure. Detailed knowledge on how to control and predict these moisture-related deformations in different species and a composite panel could provide valuable input on how to improve the utilization and fabrication of mass timber products. Novel insights into wood-moisture interactions with modifications on the grain orientation could enable new applications and more effective use of the non-standard wood species in engineered-wood or mass timber products.

Limitations and Future Research:

As mentioned above, this research presents an exploratory study relevant to the in-use performance of DCLT. We suggest that subsequent research consider the limitations of this work:

1. The studied sample specimens were cut from large-scale panels used to investigate another research objective. Since not all the large-scale specimens had minimally stressed ends after the testing, the sample size for the present study is small.
2. The less commonly used adhesive HB X452 without any primer was used in lieu of an HBS adhesive.

In addition to the insights provided in this study, the following are several examples of future research avenues that could

further advance the understanding of this topic:

1. Further similar research would initially require investigating the industry needs for DCLT fabrication with heterogenic application of wood types (hardwood and softwood), and hybrid layup configurations.
2. The dimensional measurement in this study was done by using a digital caliper with sufficient jaw length covering both species of hybrid layers. However, a more precise method could be measuring each layer individually and reporting an average dimension per species.
3. APA/ANSI PRG 320 -2019: Standard for Performance-Rated Cross-Laminated Timber [11], only provides the expected change in the thickness direction of a standard layup, and a non-hybrid CLT panel made of generic softwood species associated with a potential 2% moisture content change in the service. More investigations similar to the present study can be done with a larger sample size to provide insights into changes in both thickness and width directions by testing a variation of standard and/or hybrid large-scale CLT and DCLT panels which could possibly be an addition to the future CLT standards.

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