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Theoretical Sensitivity of Warp to Varying Layer Thickness in 5-layer Plywood[*1]

Via, Brian K.[*2], Q. Wu[*2], Ian D. Hartley[*3], Todd F. Shupe[*2],
Sangyeob Lee[*2], and Byung G. Lee[*4†]

ABSTRACT

Monte Carlo simulation was performed on theoretical models of plywood warp for southern yellow pine plywood originating from the United States. The objective of the investigation was to determine which plywood layers was more warp sensitive to veneers that were manufactured to an undesired thickness. This study found that for a balanced panel (a panel of equal target thickness for each of five layers) manufactured veneers of undesired thickness would experience minimal warp. The veneers of undesired thickness placed in the center of the plywood panel also provided a minimum change of plywood warp properties. The panel warp was very sensitive to surface veneers constructed with undesired thickness. Conversely, this study confirms that monitoring of veneer thickness and proper allocations within the plywood lay-up were critical.

Keywords : plywood warp, veneer thickness, southern yellow pine.

1. INTRODUCTION

Plywood is a wood product made from sheets of thin wood (veneer) layers glued together to form a panel. It is commonly used in furniture and building construction. A common problem that reduces or limits panel usability is warp due to the moisture cycling. Any warp deformation may decrease the design value and utility of the panel.

The design of plywood results in high dimensional stability since each veneer layer is laid down perpendicular to the axis of the previous layer. In other words, the face layer has the wood grain parallel to the panel axis while the second layer has the wood grain perpendicular to the panel axis. In most situations, shrinking or swelling of solid wood occurs more in the direction perpendicular to the cross-grain than parallel to grain. Moisture change in wood is due to changes in humidity and temperature of the surrounding environment. The difference in

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[*1] Received on April 30, 2004; accepted on June 15, 2004.

[*2] Graduate Research Assistants and Associate Professors, School of Renewable Natural Resources, Louisiana State University Agricultural Center, Baton Rouge, LA, USA.

[*3] Assistant Professor, Forestry Program, University of Northern British Columbia, Prince George, BC V2N 4Z9, Canada.

[*4] Professor, Department of Natural Resources, Yeungnam University, Gyeongsan, Gyeongbuk, Korea.

[†] Corresponding author : Byung Guen Lee (bglee211@yumail.ac.kr)

directional expansion causes internal stresses, which in turn cause warping of the board. In other words, the plywood panel warp is caused by complex viscoelastic deformations that occur when differential shrinkage (or swelling) happens due to the anisotropic behavior of each wood layer in response to moisture change. Solid wood usually has small longitudinal expansion (<0.05%) while the radial and tangential expansion is 4% and 7%, respectively, over the entire hygroscopic range (humidity changes from 0 to 100%) (Siau 1995). For veneer layers that have significant resistance within the plywood, deformation is restrained. This resistance is associated to increased modulus of elasticity (E), thickness of each layer, and grain direction of each veneer layer.

Most panel warp models assume a purely elastic response in both longitudinal and perpendicular directions (Xu and Suchsland 1996, Suchsland and Mcnatt 1986). In the longitudinal direction, this assumption is justified because of the high modulus and low expansion coefficient. However, in the cross-grain direction, wood exhibits significant plastic deformation because of the low modulus and high expansion. As a result, the elastic response only contributes 17 to 25% of the total deformation in plywood (Xu and Suchsland 1996, Lang and Loferski 1995, Lang *et al.* 1995). The assumption of pure elasticity thus causes a slight over-estimate of the radius of curvature of the warped panel, causing a slight under-estimation in overall warp (Lang and Loferski 1995, Lang *et al.* 1995). To improve the accuracy of a warp model, it is suggested that the tabulated tangential (or radial) expansion coefficients be reduced by 25% (Xu and Suchsland 1996).

Many mechanics-based equations exist to predict the radius of curvature of a warped panel, *R*, as a function of layer count, layer thickness, layer modulus, and layer expansion coefficient (Xu and Suchsland 1996, Suchsland and Mcnatt 1986). One equation, which has wide applicability due to its reduced format has the following form (Lang and Loferski 1995, Lang *et al.* 1995).

$$R=\frac{3(\sum_1^n Ei(S_i^2-S_{i-1}^2))^2-4\sum_1^n E_i(S_i^3-S_{i-1}^3)\sum_1^n E_ih_i}{6\sum_1^n E_i(S_i^2-S_{i-1}^2)\sum_1^n \alpha_i \varDelta MCE_ih_i-6\sum_1^n \alpha_i \varDelta MCE_i(S_i^2-S_{i-1}^2)\sum_1^n E_ih_i} \tag{1}$$

where S_i is the sum (Σ) from the face to the i^{th} layer, α_i is the expansion value for i^{th} layer, E_i is the modulus of elasticity at equilibrium condition (after moisture content, MC, change), $\varDelta$MC is the moisture content change, h_i is the i^{th} layer thickness and R is the radius of curvature of the warped panel. To predict deflection at center span, the following equation can be used

$$W=\frac{L^2}{8*R} \tag{2}$$

where *L* is beam length, and *W* is deflection at the center span. Since grain angle is highly influential on *E*, which effects *W*, it was assumed in this study that grain angle is exactly parallel or perpendicular to the axis dependent on veneer layer orientation (Breyer 1993). It was also assumed that each veneer had similar density, anatomical, and chemical properties. In plywood, this orientation is usually perpendicular from the adjacent layer to improve stability.

In this study, a theoretical model (i.e. equations 1 and 2) was chosen to demonstrate the potential of decreasing plywood warp by controlling layer thickness. The benefit of this study is that it demonstrates a theoretical potential to decrease the mean and variation in *W* by placing low or high thickness veneer(s) in zones of least influence. These zones include the two faces, two crossbands, and core veneer layers. Currently, many mills may know, by trial and

Table 1. Design value assumptions for each ply location

Veneer location	Thickness (mm)	Modulus of elasticity (E) (MPa)	Expansion coefficient (α)	Coefficient of variation % (COV)
Top face	2.54	11721	0.00007	10
Top crossband	2.54	3516	0.0013	10
Core	2.54	11721	0.00007	10
Back crossband	2.54	3516	0.0013	10
Back face	2.54	11721	0.00007	10

Table 2. Multiple linear regression (MLR) results predicting center deflection from 5-ply thickness

Variable	Coefficient Estimate	Standard Error	t-value	Pr > |t|	R^2
Face	4.5	0.19	23.27	<0.0001	0.98
Crossband 1	-3.8	0.16	-23.43	<0.0001	
Core	-0.09	0.14	-0.6	0.5498	
Crossband 2	3.6	0.14	24.42	<0.0001	
Back	-4.4	0.15	-28.19	<0.0001	

error, what minimum or maximum thickness to place in each layer. However, equation 1, combined with Monte Carlo simulation, provides a more efficient tool to maximize layer thickness uniformity between panels while reducing the potential for product warp.

2. EXPERIMENTAL METHODS

Equation 1 estimated curvature response as a function of each layer thickness while keeping E and α constant. Equation 2 was used to estimate *W* (deflection at center span). An increase from 9 to 12% MC was assumed. The 3% change in MC was assumed to not significantly influence E in predicting the overall variation in *W*. A Monte Carlo simulation was performed to obtain 50 center deflection values. Veneer thickness was used as the random variable for each layer with a mean thickness of 2.54 mm. A 10% coefficient of variation (COV) was assumed to generate random thickness values around each layer mean (Table 1) (Suchsland and Mcnatt 1986). The sample size needed was determined to be some point where the estimated variance in *W* leveled off with additional sampling. N = 50 exceeded this requirement by approximately 20 data points and was chosen to obtain an estimate of the distribution of W. An E = 11,721 and 2,516 MPa was assumed in the longitudinal and cross direction, respectively (Table 1) (Suchsland and Mcnatt 1986, Green *et al.* 1999). An expansion coefficient (α) represents the unitless swelling per 1% MC change as defined by Suchsland and McNatt (1986). The assumed values are listed in Table 1. Multiple linear regression analysis (MLR) was used on both scenarios to forecast *W*, as a function of random face, crossband, core, crossband, and back face thickness. MLR generated statistical t-values to demonstrate which layers influenced warp for a given scenario. It is important to note that preliminary results showed an unbalanced panel design to change the role each layer played in influencing warp variation. Therefore, the analysis in this study only refers to a specific case study where the mean panel thickness was balanced with errors in target thickness of 10%

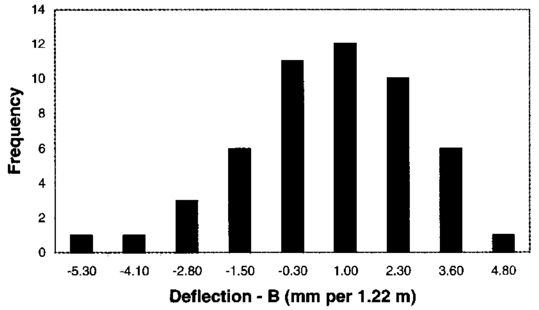

Fig. 1. Distribution of center span deflections (N=50).

COV (Table 1).

3. RESULTS and DISCUSSION

The distribution fell between -5.3 and 4.8 mm warp per 122 cm (Fig. 1). This range and variation was similar to the results of Suchsland and McNatt (1986) which was approximately ±3.1 mm per 122 cm when a COV of 5% and mean 2.54 mm mean thickness were simulated to predict W. For equal comparison, a COV of 5% percent was investigated. A COV of 5% yielded a range of variation between -2.7 to 2.1 mm per 122 cm, a range close to the ±3.1 found by Suchsland and McNatt (1986). However, in their study, no recommendation was given as to how panel performance could be improved by segregating and placing veneers into different layers as a function of thickness (Suchsland and Mcnatt 1986).

The face and crossband equally influenced *W* as interpreted by the regression coefficients (Table 2). As expected, there was a contrast between face and face crossband as shown by the reversal of coefficient signs. But just as important, the core layer was relatively uninfluential on warp variation when compared to the face and crossband, which was expected (Table 2). This finding was significant because it suggests that veneers of undesirably low or high thickness could be placed in the center layer assuming the thickness does not significantly exceed the mean and variation explored in this study. Therefore, a manufacturer could not only place veneers of abnormal thickness in the center, but also determine an allowable tolerance range for veneers to be placed in the face or crossband. Additionally, individual veneers, which have wavy thickness through the piece (high within piece variation), may be placed into the core layer as well.

By exploring the regression equation, it can be seen that if both face veneer thicknesses or both crossbands are equal, this results in no warp. This is logical from a mechanics perspective since the panel is balanced in force and resistance and assuming the layers were of equal thickness and the assumptions of Equations 1 and 2 were met.

Holding the other four layers constant, a 0.254 mm change in one face or crossband thickness resulted in a 1.016 mm per 1.22 meters change in center deflection. This same change in the core layer thickness resulted only in a change in center deflection of 0.048 mm per 1.22 meters. The predicted magnitude of change in warp was thus 20+ fold greater for the crossband and face than for the same change in core layer thickness for this specific study.

Other unbalanced panel formations are common depending on the product and manufacturing company. But the same technique applied in this case study, could be used to gain a theoretical estimate of which layers may dominate warp response. Likewise, warp tolerance limits could be recalculated to determine which classes of veneer thickness should be placed in which layer location. However, further empirical testing is recommended before implementing equation 1 in a real time manufacturing process.

4. CONCLUSIONS

In conclusion, this technique may be a powerful first step for plywood manufacturers to determine a thickness tolerance allowance for each layer in an attempt to reduce warp and increase product value. Monitoring the thickness of each veneer and re-routing it to the proper thickness class bin would have to be considered. The variation in warp was sensitive to varying face thickness and insensitive in changes of the core thickness. The warping potential of the board appeared to diminish with the increased core thickness.

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