EFFECT OF THICKNESS VARIATION ON WARP IN HIGH-TEMPERATURE DRYING PLANTATION-GROWN LOBLOLLY PINE 2 BY 4'S

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ABSTRACT

Currently, an increasing proportion of southern pine dimension lumber comes from plantations; therefore, an increase in grade, value, and volume loss from warp is expected. One factor that has not been fully explored is the effect of lumber thickness variation on warp. The primary objective of this study was to increase quantitative understanding of the effects of thickness variation on crook, bow, and twist during high-temperature kiln-drying of plantation-grown loblolly pine to determine the importance of its control on the development of warp. Plantation-grown, 2 by 4 (nominal 50- by 100-mm) loblolly pine were kiln-dried at high temperature after surfacing them in such a way as to produce certain patterns of thickness variation. One group was not surfaced, i.e., left as mill run. All boards in a second group were surfaced to the same thickness. In a third group, the boards were divided into thirds, and each third surfaced to a different thickness. In this group, boards of the same thickness were stacked in vertical alignment to exaggerate the effect of the thickness variation. The fourth group differed from the third group in that the three thicknesses were randomly placed in the package. The extreme thickness variations did aggravate warp, especially twist. As a result of better sticker contact, thick boards warped less than did thin boards. However, even with perfect sticker contact, a substantial amount of warp developed, indicating that control of thickness variation can reduce but will not eliminate warp. Correlation of warp with board characteristics suggests that boards containing pith warp more than ones without pith, and boards sawn from near the center of the tree warp more than boards farther from the center of the tree.

Keywords: Warp, bow, crook, twist, loblolly pine.

INTRODUCTION

The occurrence of excessive warp—bow, crook, and twist—during drying of lumber sawn from fast-grown southern pines was recognized long ago by Koehler (1938). In current times, we are seeing an increasing proportion of southern pine dimension lumber coming from plantations. Therefore, we can expect an increase in grade, value, and volume loss from warp.

Over the years, several studies have been designed to increase our understanding of the causes of warp in plantation loblolly pine as well as in young-growth timber from other pine species, such as ponderosa and radiata

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pine. Causes studied include the effects of fibril angle, percentage of juvenile and compression wood, annual ring characteristics, distance from pith, grain deviation, and lumber grade.

Several studies to identify the causes of warp have been reported. Gaby (1972) concluded that southern pine studs containing pith were prone to warp considerably in excess of grading rules allowances. He also found that warping problems were associated with the presence of mild compression wood in the first three or four growth rings surrounding the pith for half or more of the stud length.

Balodis (1972) found that twist was proportional to the ratio of spiral grain angle to the distance from the pith of the tree, and he developed a regression equation to describe this relationship. Boards close to the pith and with a high degree of spiral grain twisted most.

Shelly et al. (1979) found that the presence of pith in young-growth ponderosa pine studs had the greatest effect of all the variables they studied on bow, crook, and twist. Although the percentage of heartwood in a stud did not affect warp, studs with a layer of heartwood along one edge were prone to severe crook. This was caused by the slower rate of heartwood drying, which leads to an imbalance in the rate of shrinkage on opposite edges. Other factors studied, such as density, knots, and grain angle, were not major factors in severe warp. Their material contained little compression wood, so they were not able to show any effect.

Voorhies and Blake (1981) found that juvenile and compression wood in young-growth ponderosa pine were the main causes of warp. They caused warp because of greater longitudinal shrinkage than that of mature or normal wood. During drying, the face or edge of a board with juvenile or compression wood shrunk more in length than did the opposite face or edge with normal wood, thus the board warped. The greatest cause of warp in their study was in boards cut from butt logs that contained the greatest amount of compression wood. The proportion of heartwood and sapwood had no effect on warp. Knots may have affected warp.

In another study, Voorhies and Groman (1982) found a strong relationship between longitudinal shrinkage in juvenile wood and fibril angle. The greater the fibril angle, the greater the longitudinal shrinkage.

Mishiro and Booker (1988) found that twist in radiata pine was strongly related to spiral grain. However, bow, crook, and twist did not relate well to density, growth ring width, or distance from the pith.

Beard et al. (1993) studied the impacts of growth characteristics on warp in grades No. 2 and 3 southern pine standard 38- by 140-mm (nominal 2- by 6-in.; hereafter called 2 by 6's) lumber. They found that the amount of compression wood affected bow and crook, and the amount of wane affected crook. Juvenile wood, distorted grain, slope of grain, specific gravity, and knots accounted for 9 or less percent of the observed bow, crook, and twist.

Milota (1992) dried Douglas-fir 2 by 6's from both large- and small-diameter trees by slow and fast kiln schedules at conventional and elevated temperatures. Warp in any given board was not strongly related to the percentage of juvenile wood, ring count, final moisture content, or density. Boards from the small-diameter logs twisted more than those from the large-diameter logs.

One factor that has not been fully explored is the effect of lumber thickness variation on warp. If thickness variation is excessive, thin boards will not receive full restraint in the lumber package and will warp (Fig. 1). It has long been assumed that good contact between stickers and boards is effective in minimizing warp, but there does not appear to be information available to quantify this assumption. The primary objective of this study was to increase our quantitative understanding of the effects of thickness variation on crook, bow, and twist during high-temperature kiln-drying of plantation-grown loblolly pine 2 by 4's (nominal 50 by 100 mm) in an attempt to de-

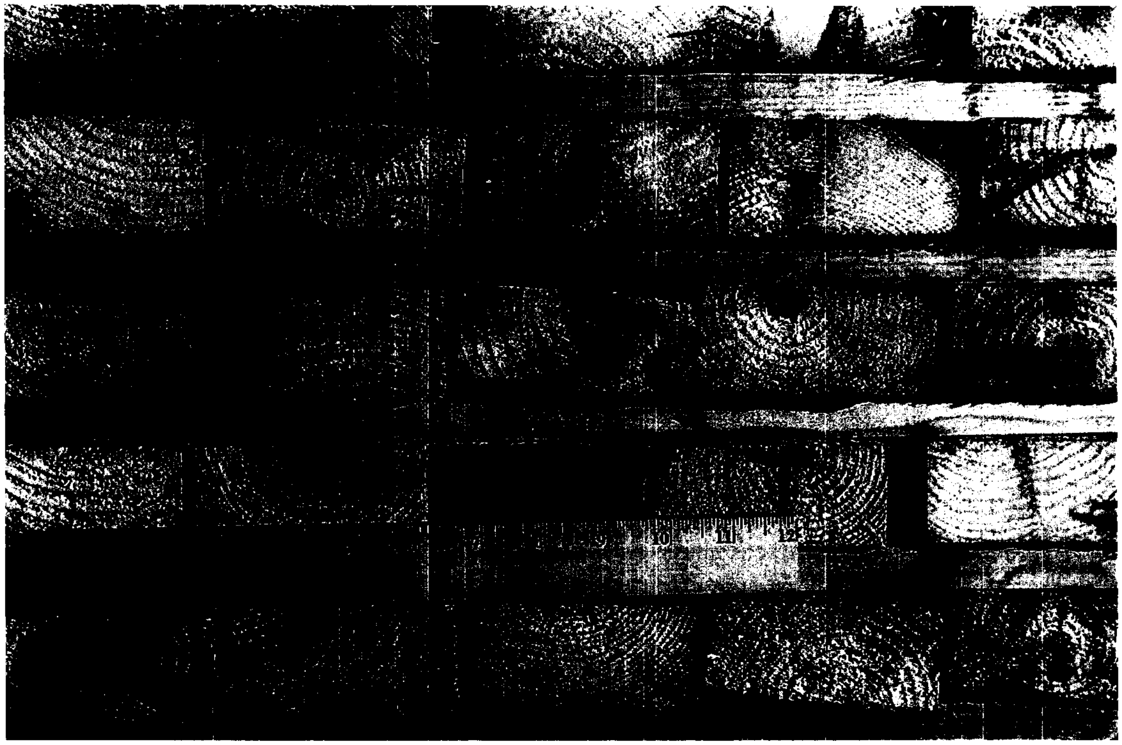

FIG. 1. End view of lumber package showing twist in thin boards that do not make contact with stickers.

termine the importance of its control on the development of warp. A secondary objective was to examine the effects of other board characteristics on warp.

EXPERIMENTAL

Loblolly pine 2 by 4's, 2.44 m (8 ft) long, were obtained from plantations in Georgia and South Carolina. Upon arrival in Madison, each 2 by 4 was numbered in sequence. Photographs of each end of each 2 by 4 were taken at close enough range that the growth ring detail in each board was apparent (Fig. 2). These photographs were used to make the following observations on both ends of each board: presence or absence of pith, growth ring count (number of rings per mm), growth ring orientation, and distance from the pith. Growth ring orientation was classified as flat (growth rings predominately parallel to the wide face, 45 degrees (growth rings approximately 45 degrees to the wide face), quarter (growth rings approximately parallel to the edge), and FQ45 (flat on one end and quarter on the other end). Distance from the pith was determined from a template of arcs of known radius. The distance from the pith was taken as the radius of the arc that most closely matched the curvature of the growth rings.

After these characteristics were recorded, the boards were divided into seven groups of 234 boards each. The division was made such that there was an approximately equal distribution of the values of the characteristics in each of the seven groups. The boards were stacked in packages of 117, double-wrapped in polyethylene sheets, and stored at −23°C (−10°F) until used.

Four of the seven groups were used in this study, and each of the four was assigned to a kiln run. In the first kiln run, the boards were dried mill run; that is, no modification was made to their thickness; this group was designated MR. In the second kiln run, each

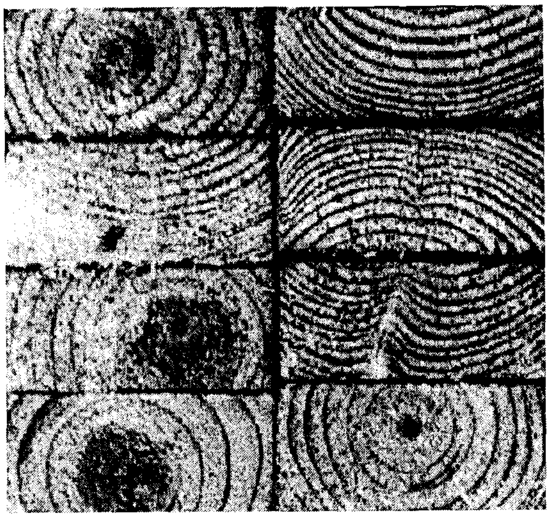

FIG. 2. End view of boards showing growth ring orientation.

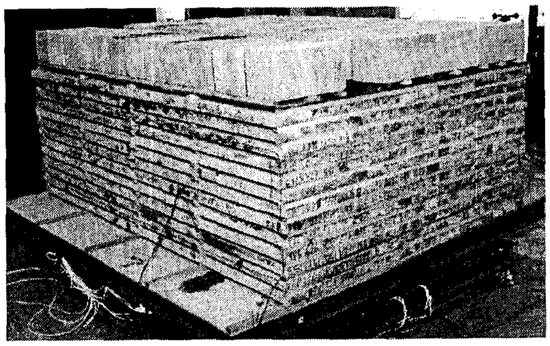

FIG. 3. Package of loblolly pine 2 by 4's with top load ready to be pushed into the dry kiln.

board was surfaced to 42.4 mm (1.67 in.) thick to represent zero thickness variation; this group designation was ZV.

In the third kiln run, a third of the boards were surfaced to 42.4 mm thick, a third to 39.4 mm (1.55 in.), and a third to 36.3 mm (1.43 in.). This thickness variation was intended to represent a poorly controlled mill. Although a poorly controlled mill would be unlikely to produce three discrete thicknesses from 36.3 to 42.4 mm, it did represent a worst-case outcome in terms of poor sticker contact. To further accentuate the worst-case outcome, the boards were stacked in an ordered arrangement of thicknesses. The first board in each layer was 42.4 mm thick, the second was 39.4 mm, and the third was 36.3 mm. This pattern was then repeated for the entire 18 positions in each layer. In the fully assembled kiln package (Fig. 3), which was 13 layers high, all 42.4-mm boards were in vertical alignment, as were all 39.2- and 36.2-mm boards. To symbolize the pattern of three thicknesses and ordered arrangement, this group designation was 3o.

In the fourth kiln run, the boards were surfaced the same as the third kiln run. Instead of the orderly distribution in the package, each of the 234 board positions in the package (13 layers of 18 boards each) was randomly assigned one of the three thicknesses. This group designation was 3r. This configuration was intended to closely approximate how variable thicknesses would be distributed in a package, again recognizing that in a real situation the variation in thicknesses would be more continuous than three discrete ones.

Before stacking, each board was weighed. The package was 1.83 m (6 ft) wide, with 19-mm- (¾-in.) thick stickers placed every 0.6 m (2 ft). Plywood was placed on the stickers over the top layer, and concrete blocks were placed on the plywood. The total weight of the blocks was about 2.39 kPa (50 lb/ft^2), which is equivalent to the weight of about 9 layers wet and 16 layers at final moisture content. Figure 3 shows a package ready to be pushed into the dry kiln. Dry kiln conditions were 116°C (240°F) dry-bulb temperature, 82°C (180°F) wet-bulb temperature, and 5.1 m/sec (1,000 ft/min) air velocity. Fan direction was reversed every 3 hours.

Drying was monitored by the changing weight of the package, as measured by four load cells, one at each corner of the package platform. Target final moisture content was 15%. Drying time varied from 17 to 21 hours. After drying, the weighted package was allowed to cool for 16 hours. After cooling, each board was weighed and bow, crook, and twist were measured to the nearest 0.79 mm ($\frac{1}{32}$ in.). Bow and crook were measured at the

TABLE 1. *Results of group comparisons of warp in high-temperature drying of loblolly pine 2 by 4's. Shown are the average, standard deviation, and percentage of boards that exceed warp limits of the SPIB (1977) grading rules.*[a]

Group	Bow (mm)	Crook (mm)	Twist (mm)	Any form
MR (mill run)				
Average (mm)	8.65	4.60	1.62	—
Standard deviation (mm)	7.40	3.49	2.12	—
Exceed limits (%)	21.8	18.1	1.3	31.6
ZV (zero variation)				
Average (mm)	7.94	5.24	1.99	—
Standard deviation (mm)	6.81	4.60	2.85	—
Exceed limits (%)	20.9	22.2	1.7	35.5
3o (3, ordered)				
Average (mm)	10.00	6.03	3.55	—
Standard deviation (mm)	9.12	5.74	3.84	—
Exceed limits (%)	25.6	25.6	7.7	43.2
3r (3, random)				
Average (mm)	9.37	6.51	2.85	—
Standard deviation (mm)	7.65	5.49	3.73	—
Exceed limits (%)	21.8	28.6	4.7	43.2

[a] 1 in. = 25.4 mm.

points of maximum deviation, and twist was measured as the elevation of the fourth corner with the other three corners held tight to the reference surface. The boards were then restacked and oven-dried at 107°C (225°F) for 4 days so that the moisture content of each board could be calculated.

RESULTS

Comparison of groups

The average and standard deviations of bow, crook, and twist of each of the four groups are shown in Table 1. The percentage of boards not meeting the Southern Pine Inspection Bureau's (1977) STUD grade because of excessive warp (bow = 12.7 mm, crook = 6.4 mm, and twist = 9.5 mm) is also shown in Table 1. The results of tests for statistical significance are shown in Table 2. Figure 4 shows a typical distribution of warp—most of the warp clustered around the average and a slight skew toward high values of warp. Based on the degree of restraint, we expected the amount of warp in each of the four groups to follow a certain pattern. Group ZV should

TABLE 2. *Results of tests to determine significance of differences between groups: yes indicates groups are statistically different at the 0.05 confidence level (Wilcoxon test for equality).*

Group comparison	Statistically different		
	Bow	Crook	Twist
ZV compared with MR	No	No	No
ZV compared with 3o	Yes	No	Yes
ZV compared with 3r	Yes	Yes	Yes
MR compared with 3o	No	Yes	Yes
MR compared with 3r	No	Yes	Yes
3o compared with 3r	No	Yes	Yes

have shown the least warp because of near perfect sticker contact. Next best should have been group MR because, although there was some thickness variation, it was not as much as in groups 3o and 3r. Figure 5 shows the frequency distribution of thicknesses in group MR. The total range, from thinnest to thickest, was 3.6 mm (0.14 in.). However, from Fig. 5, we can see that the majority of boards were between about 45.2 and 47.2 mm (1.78 and 1.86 in.) thick—a difference of only 2.0 mm (0.08 in.). This is considerably less than the 6.1-mm (0.24-in.) difference between the thinnest and thickest boards in groups 3o and 3r.

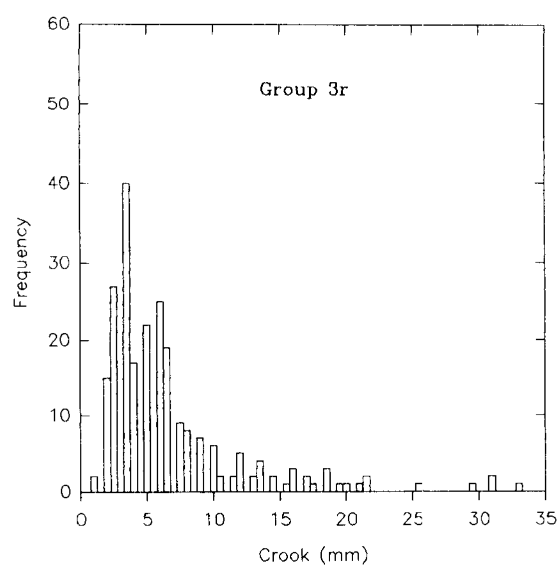

FIG. 4. Typical distribution of warp of 234 boards in group 3r.

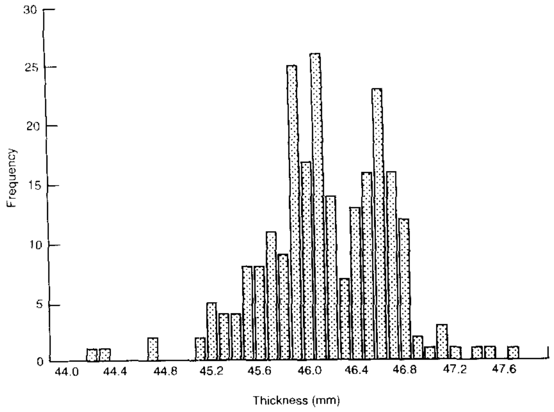

FIG. 5. Distribution of board thicknesses in the mill run (MR) group.

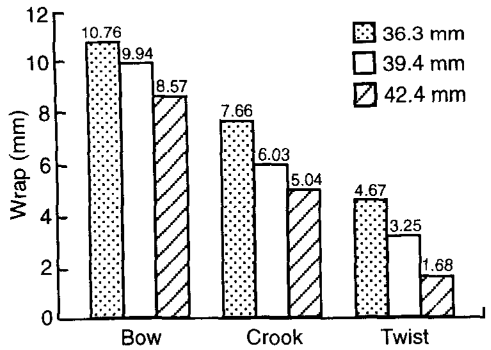

FIG. 6. Effect of board thickness on crook, bow, and twist in experimental groups 3o and 3r.

Group 3o should have shown the worst warp because of the maximum number of occurrences of boards exposed to the thickness differences of 3.0 or 6.1 mm. Group 3r should have been somewhat better than group 3o because of fewer boards exposed to these thickness differences.

Bow.—All bow average results were in the order expected. The differences between group ZV and groups 3o and 3r were statistically significant. None of the other differences was statistically significant.

Crook.—The average crook for group ZV was greater than for group MR, but the difference was not statistically significant. Groups ZV and MR had significantly less crook than groups 3o and 3r, with the exception of the comparison between group ZV and group 3o, where the smaller crook of group ZV was not statistically significant. Crook in group 3o was significantly less than in group 3r. In general, the crook behavior did not follow expectations beyond the general trend of more crook in groups 3o and 3r than in MR and ZV.

Twist.—The average twist of group ZV was greater than group MR, but not statistically different. Groups ZV and MR had significantly less twist than either group 3o or 3r. Group 3o had significantly greater twist than group 3r. In general, the twist response followed expectations.

Comparison of thick and thin boards

Figure 6 shows a comparison of warp between boards of the three thicknesses in groups 3o and 3r. The trend clearly is for the thin boards to develop more warp than the thick boards. Details are given in Tables 3 and 4. Data for group MR are also included in Table 3. This group was divided into the thinnest one third, the thickest one third, and the middle one third for the purpose of analysis. The differences in bow between the various thick-

TABLE 3. *Average results of the effect of board thickness on warp and final moisture content in high-temperature drying of loblolly pine 2 by 4's.*[a]

Group	Bow (mm)	Crook (mm)	Twist (mm)	Moisture content (%)
3o				
36.3 mm	11.01	7.43	5.24	10.7
39.4 mm	10.94	6.00	4.02	13.8
42.4 mm	8.38	4.48	1.40	18.5
3r				
36.3 mm	10.50	7.89	4.10	11.3
39.4 mm	8.94	6.06	2.48	15.3
42.4 mm	8.76	5.60	1.95	17.2
MR				
Thinnest third	9.49	4.74	1.52	15.2
Middle third	8.49	4.46	1.51	16.2
Thickness third	8.03	4.59	1.87	16.7

[a] 1 in. = 25.4 mm.

TABLE 4. *Significance of differences between thicknesses: yes indicates that results are statistically different at the 0.05 significance level (Kruskal-Wallis one way ANOVA on ranks, nonparametric, and Student-Newman-Keuls test for pairwise comparisons).*

	Statistically different			
Group	Bow	Crook	Twist	Moisture content
3o				
36.3 compared with 42.4 mm	No	Yes	Yes	Yes
36.3 compared with 39.4 mm	No	Yes	Yes	Yes
39.4 compared with 42.4 mm	No	No	Yes	Yes
3r				
36.3 compared with 42.4 mm	No	Yes	Yes	Yes
36.3 compared with 39.4 mm	No	Yes	Yes	Yes
39.4 compared with 42.4 mm	No	No	Yes	Yes
MR				
Thin compared with thick	No	No	No	No
Thin compared with medium	No	No	No	No
Medium compared with thick	No	No	No	No

nesses were not statistically significant, but most of the other differences for groups 3o and 3r were statistically significant (Table 4). None of the comparisons between thicknesses for group MR showed a statistically significant difference.

The main factor responsible for the increase in warp in the thinner boards was probably the lack of sticker contact, thus a reduction in restraint. However, another factor may be involved. As Table 3 shows, the thinner boards dried to a lower moisture content than did the thicker boards. Final moisture content in groups 3o and 3r was 7% to 8% less in the thinner boards. We expected that warp would increase as final moisture content decreased because of greater shrinkage. Figure 7 shows a typical relationship between warp and final moisture content. Despite the considerable scatter in the data, warp tended to increase as final moisture content decreased. Regression analyses were conducted on the three forms of warp and final moisture content for group ZV. The choice of group ZV restricts the results to the effect of final moisture content. Based on these regressions, we expected to see a 20% to 30% difference in warp as a result of the 7% to 8% moisture content difference between the thick and thin boards. Table 5 gives the percentage of increase in warp caused by thickness variation. The actual percentage differences for group 3o were 31% for bow, 66% for crook, and 274% for twist. Thus, moisture content could account for much of the bow difference, but relatively small portions of the crook and twist difference.

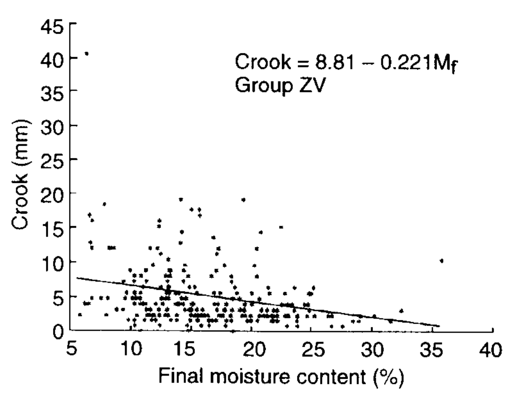

FIG. 7. Effect of final moisture content on crook. $R = 0.101$.

Importance of thickness variation to total warp

Based on the evidence presented, it appears that excessive thickness variation does aggravate warp. The question then remains: How important is this contribution to total warp?

TABLE 5. *Increase in warp as a result of thickness variation in high-temperature kiln-drying of loblolly pine 2 by 4's.*

Comparison	Increase in warp (%) Bow	Crook	Twist
By groups			
ZV compared with 3o	25.9	15.1	78.4
ZV compared with 3r	18.0	24.2	30.2
SV compared with MR	8.9	−12.2	−18.6
Average	17.6	9.0	30.0
By board thickness			
42.4 compared with 39.4 mm			
3o	30.5	33.9	187.1
3r	2.1	8.2	27.1
42.4 compared with 36.3 mm			
3o	31.4	65.8	274.3
3r	19.9	40.9	107.8
Average	21.0	37.2	149.1

We considered group ZV as the control group; that is, none of the warp observed in this group was caused by thickness variation. We also considered the thick boards in groups 3o and 3r to be controls in this same sense. As discussed previously, these comparisons represent the worst case—an upper limit—because of the artificial nature of the deliberately manufactured thickness variations and stacking methods. The comparisons are shown in Table 5, which shows the percentage increase in warp over the controls caused by the thickness variation. The results suggest that twist was aggravated by thickness variation much more than either bow or crook, with some comparisons well over a 100% increase. The results also suggest that crook may be slightly more affected by thickness variation than bow.

Effect of board characteristics

Pith.—The effect of the presence or absence of pith on warp is shown in Table 6. In all comparisons, warp was greater when pith was present. Even though only four of the twelve comparisons were statistically significant, the evidence seems to indicate that the presence of pith increases warp.

Growth ring orientation.—Table 7 summarizes the effect of growth ring orientation on warp. Only one comparison showed a statistically significant difference. In group 3r, twist in quarter sawn was significantly greater than for any other ring orientation. There does not seem to be any rational explanation for this observation other than there were so few quarter-sawn boards that an aberration in results was more likely than in groups with many ob-

TABLE 6. *Effect of presence or absence of pith on warp in high-temperature dried loblolly pine 2 by 4's; * indicates a statistically significant difference (Mann-Whitney rank sum test, nonparametric).*[a]

	Bow (mm)		Crook (mm)		Twist (mm)	
Group	Pith	No pith	Pith	No pith	Pith	No pith
MR	9.09	8.30*	5.15	4.10	1.63	1.63
ZV	8.56	7.32*	5.70	4.70	2.56	1.47*
3o	10.45	9.70	6.63	5.57	4.27	2.91
3r	9.80	9.80	7.27	6.49	3.45	2.32*

[a] 1 in. = 25.4 mm.

TABLE 7. *Effect of growth ring orientation on warp in high-temperature dried loblolly pine 2 by 4's; * indicates a statistically significant difference from the other growth ring orientations (Kruskal-Wallis one way ANOVA on ranks, nonparametric).*[a]

Group	Bow (mm)	Crook (mm)	Twist (mm)
MR			
Flat	8.02	4.28	1.54
45 degrees	9.06	5.29	1.84
Quarter	11.11	5.84	1.42
FQ45	8.70	4.12	1.65
ZV			
Flat	7.42	4.60	1.71
45 degrees	7.06	5.19	1.96
Quarter	7.31	4.99	3.86
FQ45	9.40	5.96	2.02
3o			
Flat	9.55	5.65	3.07
45 degrees	9.83	5.99	3.39
Quarter	9.46	6.55	6.15
FQ45	9.45	6.57	3.87
3r			
Flat	8.90	5.87	2.31
45 degrees	10.19	7.45	2.48
Quarter	10.52	9.53	6.70*
FQ45	9.40	6.29	3.14

[a] 1 inch = 25.4 mm.

TABLE 8. *Effect of distance from pith (D in mm), growth ring count (R/mm), product of distance and ring count (D × R/mm), and specific gravity on warp in high-temperature dried loblolly pine 2 by 4's. Values are correlation coefficients as determined by Spearman rank order correlation analysis, nonparametric; * indicates a statistically significant correlation at the 0.05 confidence level.*

Group	D	R/m	D × R/mm	Specific gravity
MR				
Bow	−0.070	−0.280*	−0.153	0.046
Crook	−0.043	−0.170*	−0.099	0.048
Twist	−0.059	0.049	−0.026	−0.068
ZV				
Bow	−0.121	−0.243*	−0.186*	0.091
Crook	−0.060	−0.095	−0.081	0.241*
Twist	−0.104	−0.093	−0.114	−0.182*
3o				
Bow	−0.085	−0.247*	−0.138	0.172*
Crook	−0.036	−0.151	−0.073	0.095
Twist	−0.151	0.048	−0.112	−0.051
3r				
Bow	−0.199*	−0.283*	−0.239*	0.001
Crook	−0.142	−0.196*	−0.175*	−0.002
Twist	−0.259*	−0.220*	−0.277*	−0.320*

servations. We expected quarter-sawn boards to show more crook than other orientations because juvenile wood could be oriented on either edge of a board. The higher average values for crook in groups MR, 3o, and 3r weakly support this idea. In ZV, where zero variation might supply enough crook restraint to minimize warp, crook in quarter-sawn boards was not greater than in several other ring orientation boards.

Another weak observation (because of lack of statistical significance and small differences in averages) is the difference in warp of flat-sawn boards compared with 45 degree and FQ45 boards. In eleven of the twelve comparisons, flat-sawn boards had less warp than the 45 degree boards, and 10 of the 12 boards had less warp than the FQ45 boards.

Distance, ring count, and specific gravity.—The effects of distance from the pith, growth ring count, product of distance and growth ring count, and specific gravity are shown in Table 8. The statistically significant correlation coefficients do not show many patterns except that ring count appears to have an effect on warp, especially on bow. These correlation coefficients are all negative, meaning that warp is greater at small ring counts, i.e., near the pith. Even though few of the correlations coefficients were significant, most of them for distance from the pith and ring count were negative. This supports the idea that warp is greater in boards sawn from near the center of the log. The correlation coefficients for the effect of specific gravity on warp are contradictory; some are positive and some are negative. We would expect them to be negative because juvenile wood is known to have lower specific gravity than mature wood.

CONCLUSIONS

Some results in this study to determine the effects of thickness variation on bow, crook, and twist in kiln-drying plantation-grown loblolly pine 2 by 4's were not conclusive because of lack of statistical significance. However, many observations were statistically significant, and even when not, some comparisons of averages suggest certain trends. It seems clear that the extreme thickness variation generated in this study aggravates warp, especially twist. It is also clear that thin boards warped more than thick boards that made good sticker contact. However, even with perfect board-to-sticker contact, a substantial amount of warp still develops, which indicates that there is a limit to the effectiveness of thickness variation control in reducing warp. These results represent the worst possible effect of thickness variation because of the artificial nature of the board thicknesses generated for the study, and should be interpreted in that light.

The effects of board characteristics, such as presence or absence of pith, growth ring orientation, growth ring count, and distance from the pith, were not clear in many cases. It seems justified to conclude that (1) boards containing pith warped more than boards containing no pith, and (2) boards nearer to the pith warped more than boards cut from further away from the pith.

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