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Effect of Moisture Content on Warp in Hardwood 2 by 6's for Structural Use

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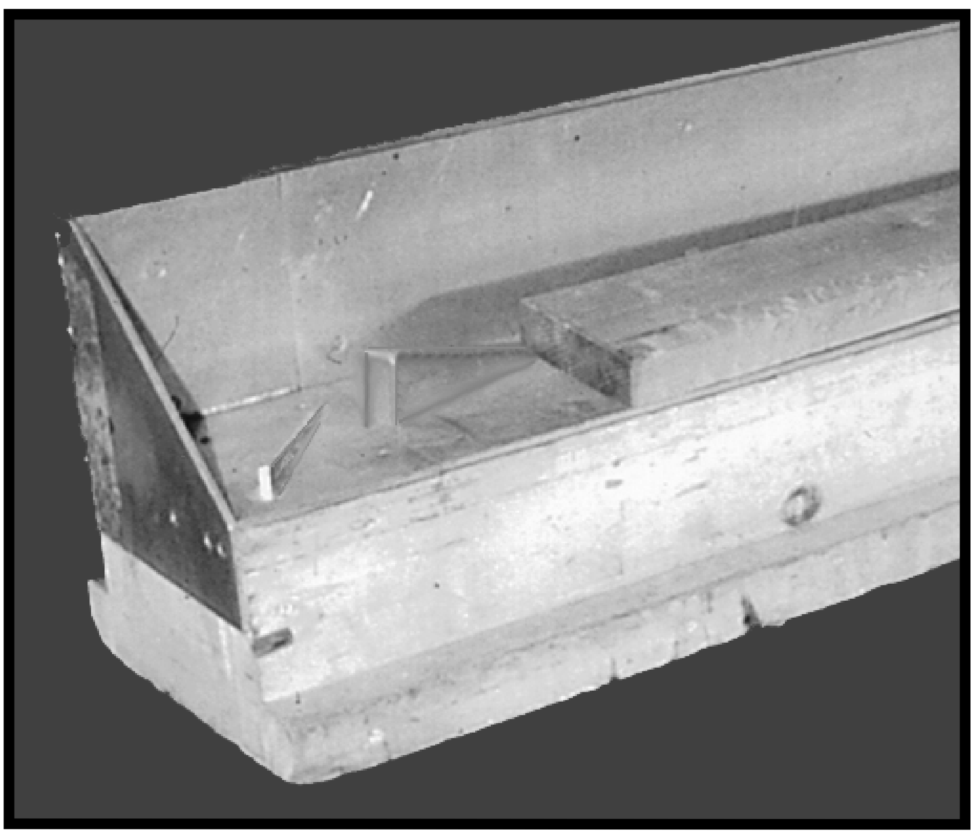

Abstract

Sugar maple (*Acer saccharum*), red maple (*Acer rubrum*), and yellow birch (*Betula alleghaniensis*) 2 by 6's were dried and evaluated for warp as it affects ability to meet softwood dimension lumber grading rule requirements for warp. In the first part of the study, sugar maple was kiln-dried to three levels of final moisture content: 27%, 19%, and 12%. Warp during kiln drying increased as final moisture content decreased. Following kiln drying, the lumber was planed and then equilibrated in 12% equilibrium moisture content conditions. Warp during equilibration generally increased as the final moisture content after kiln drying increased. Crook, bow, and twist did not increase enough during equilibration to cause much structural lumber grade loss from warp. However, the percentage of boards still meeting structural lumber grade limits for cup fell to about 80%. In the second part of the study, sugar maple, red maple, and yellow birch 2 by 6's were air- and predried to 27% moisture content and, in general, did not suffer much grade loss during equilibration.

Keywords: drying, hardwoods, structural lumber, warp

Contents

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Effect of Moisture Content on Warp in Hardwood 2 by 6's for Structural Use

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Introduction

Structural products such as trusses and I-joists are potential high value uses for lumber that is low grade by hardwood lumber grading rules. The use of hardwood lumber for structural uses requires that we rethink the drying process. Traditional hardwood kiln schedules were developed for appearance products such as furniture, cabinets, millwork, and flooring. They were necessarily mild, and thus slow, schedules to virtually eliminate any checking or discoloration. But checks and discoloration are not defects in structural lumber, so we have the opportunity to develop schedules that are accelerated and thus more efficient than the traditional hardwood schedules. A previous study (Simpson and others 1998) showed that the schedule for maple 2 by 6's could be accelerated to almost a 50% reduction in drying time without detracting from use as structural lumber. That previous study and this current study are part of a larger program to evaluate the feasibility of hardwoods for structural applications.

As a continuation of developing an optimum schedule, we wanted to investigate the effect of final moisture content on warp and its influence on grade in sugar maple 2 by 6's. Softwood structural lumber is generally dried to a moisture content of 15% to 19%, even though it is expected to eventually dry to 10% to 12% (and even less in the arid southwest) in use. Reasons for this practice are to shorten drying time and to minimize downgrade from warp that is thought to increase as final moisture content decreases. A potential problem associated with drying to a higher final moisture content than what the lumber will later attain is warp during post-kiln moisture loss that may cause grade loss or adversely affect truss or joist construction and performance.

This study was in two parts. One part involved kiln drying sugar maple 2 by 6's at the USDA Forest Service, Forest Products Laboratory in Madison, Wisconsin, and the other part involved air drying and predrying sugar maple, red maple, and yellow birch 2 by 6's in cooperation with Michigan Technological University and a lumber mill in South Range, Michigan. The objectives of the kiln drying part of the study were to determine if warp in sugar maple 2 by 6's increases as final moisture content immediately after kiln drying decreases and if warp develops during post-kiln moisture loss as the lumber equilibrates to ambient equilibrium moisture content (EMC) conditions. In the second part of the study, we explored the warp characteristics of other northern hardwoods and other drying methods, but to keep the study within manageable size, we examined only one level of final moisture content after air and low temperature, forced-air predrying and before equilibration to ambient EMC.

Background

Although, apparently, there are no data in the literature on the effect of final moisture content or post-kiln drying on warp of hardwood lumber, there are some available for softwood lumber. Bassett (1973) studied the effect of final moisture content on degrade in kiln drying Douglas-fir dimension lumber. He found that degrade increased with decreasing final moisture contents between 20% and 10%. He did not distinguish what types of degrade increased, but presumably some of the degrade was warp, in addition to increased degrade caused by splitting at the planer. Koch (1971) kiln dried southern pine 2 by 4's at high temperature to a final moisture content of 9% and then observed their warp (crook, bow, and twist) 48 hours out of the kiln, after planing, after exposure to 81^{o}F (27^{o}C) and 87% relative humidity (18.7% EMC), and then after exposure to 130^{o}F (54^{o}C) and 10% relative humidity (1.6% EMC). He found an increase in all forms of warp in the 48 hours after removal from the kiln, then a decrease after planing, a further decrease after exposure to the high humidity, and then a large increase after exposure to the low humidity. Markstrom and others (1984) kiln-dried young growth (70–80 years old) ponderosa pine studs to two of the common softwood standards (below 19% or an average of 15%) and measured both grade and the three forms of warp after drying. With the arid southwest in mind as the likely market for these studs, they then further dried the studs to 9% and then 6% moisture content, measuring grade and warp at each level, to simulate the conditions the studs would probably go through in transit or service. As expected, all forms of warp increased and grade recovery decreased as the studs were further dried.

Materials and Methods

Sugar maple, red maple, and yellow birch 2- by 6-in. (51- by 152-mm) boards, 8 ft (2.4 m) long, were taken from the production line of a mill in the Upper Peninsula of Michigan. The lumber was sawn from cants remaining after the high grade boards were sawn from the outer parts of the logs. The hardwood lumber grades of the 2 by 6's (NHLA 1994) were 3A, 3B, and Below Grade.

For the kiln-drying part of the study (sugar maple only), the boards were divided into three groups of 119 boards each—one group to be dried to 27% moisture content, another to 19%, and the third to 12%. The kiln schedule used (Table 1) started at a dry-bulb temperature of 160°F (71°C) and a wet-bulb temperature of 153°F (67°C). Each of the three groups was kiln-dried separately, with eight kiln sample boards (Forest Products Laboratory 1991), four on each side of the stacks, to monitor moisture content for schedule changes and to estimate when the kiln charges reached their desired final moisture content.

For the air and predrying part of the study, 105 boards of each of the three species were taken from the line for air drying and the same number for predrying (except 128 boards were taken for air drying sugar maple). Four sample boards were selected to monitor moisture content. Final moisture content, as determined by kiln samples, after air and predrying was 27%.

Table 1—Kiln schedule for drying hard maple 2 by 6's

Moisture content (%)	Dry-bulb temperature (°F	(°C))	Wet-bulb temperature (°F	(°C))	EMC (%)
50+	160	(71)	153	(67)	13.4
50 to 40	160	(71)	150	(66)	11.5
40 to 35	160	(71)	145	(63)	9.4
35 to 30	160	(71)	135	(57)	6.8
30 to 25	170	(77)	130	(54)	4.4
25 to final	180	(82)	130	(54)	3.3

Crook, bow, and twist were measured on each of the boards before drying, after drying but before planing, and after planing (Fig. 1). Boards were planed to 1.5 by 5.5 in. (38 by 140 mm). The boards that were kiln-dried were then stacked on stickers and equilibrated in conditions that resulted in 12% EMC. The boards that were air- or predried were left to equilibrate with outdoor ambient conditions, which resulted in boards reaching 12% to 14% EMC. After equilibration, crook, bow, twist, and cup were measured again.

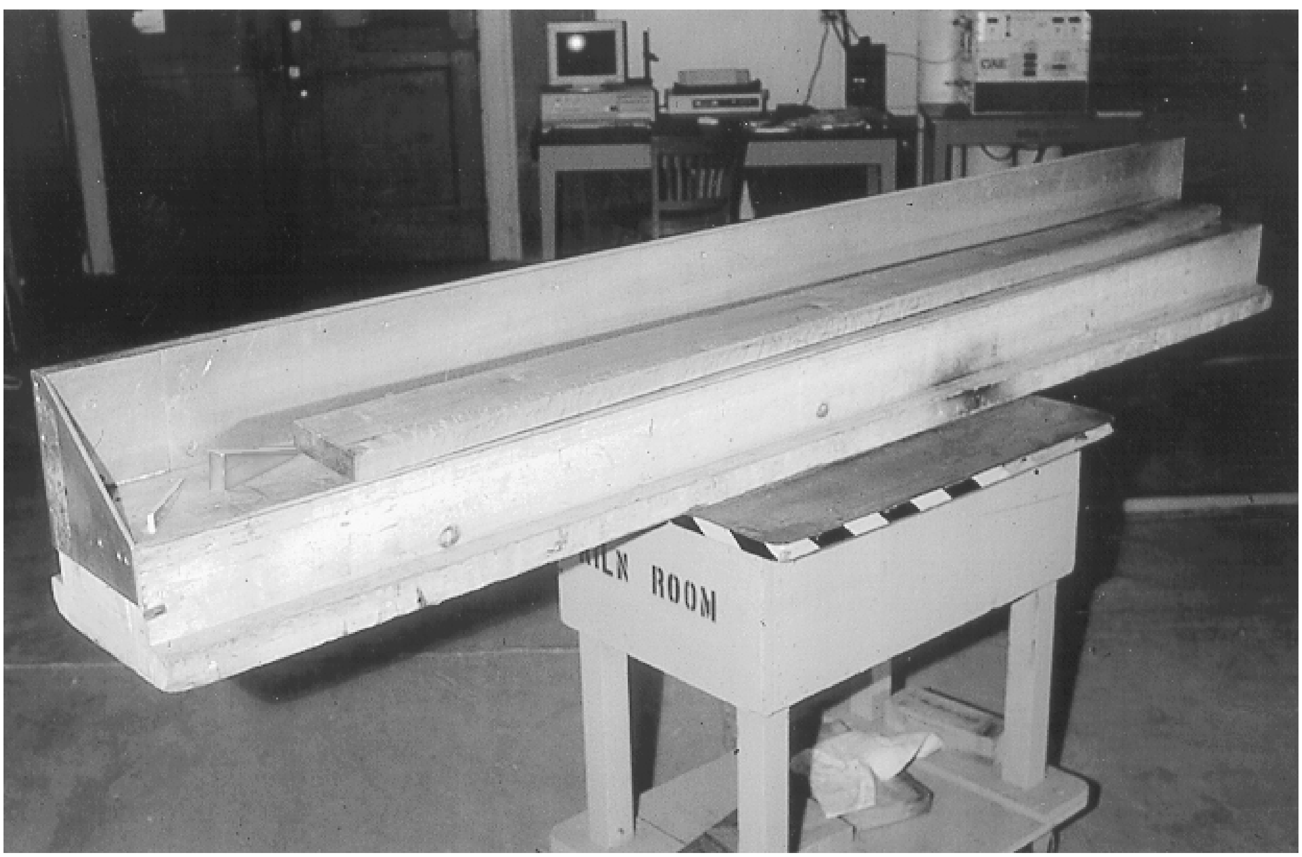

Figure 1—Warp measuring table and wedges used for measuring twist.

Results and Discussion

Drying and Equilibration Times

Table 2 shows the drying times to the nominal final moisture contents. Kiln-drying times for sugar maple ranged from 5.6 days required to dry to 12% moisture content to 3.3 days to dry to 27%. Predrying times to 27% moisture content ranged from 9 days for sugar maple to 17 days for yellow birch. Air-drying times to 27% moisture content were about 25 days for all three species. Equilibration curves are shown in Figure 2.

Warp Measurements

We were concerned with two aspects of warp during drying and equilibration. First, we were concerned with the net warp that occurred during drying; that is, the difference between warp in the lumber before drying, which was presumably caused by growth stresses unbalanced by sawing, and warp after drying but before planing. Similarly, the net warp after equilibration is the difference between warp measured immediately after planing (not all warp is necessarily eliminated by planing) and after equilibration. The second aspect we were concerned with was gross warp, from the standpoint of utility and meeting grade warp requirements; that is, the actual state of warp at the time of interest, not the net amount of change. The gross warp values are summarized in Table 3. Table 4 shows the net warp that occurred during drying and equilibration. The values are the averages of the absolute value of the changes in warp during either drying or equilibration. Use of absolute values was necessary because sometimes warp was more and sometimes it was less after drying or equilibration than it was before, and the absolute value best describes the change that occurred. Therefore, the differences between before and after warp measurements in Table 3 (gross values) are not always the same as those in Table 4. Bow in particular was affected in this way because of the common presence of bow before the lumber was dried.

The amount of net warp that occurred during kiln drying sugar maple is shown in Table 5. These warp values are the net warp; that is, the difference between warp measurements before drying and after drying but before planing. The data clearly show that all forms of warp increase as final moisture content decreases. The amount of warp that occurred in sugar maple during equilibration after kiln drying and planing is shown in Table 6. The values shown are the differences in warp measured after drying and after planing and then after equilibration. The reason warp developed in the boards dried to 12% is the distribution of final moisture contents. Even though the average final moisture content was estimated (by kiln samples) to be 12%, the distribution of final moisture contents results in some boards being at a higher moisture content (Simpson and others 1998) and thus having the potential to warp during equilibration to 12%.

Table 2—Kiln-, pre-, and air-drying times for hardwood 2 by 6’s

Species and drying method	Drying time (days)
Sugar maple	
Kiln-dried to 27%	3.3
Kiln-dried to 19%	4.3
Kiln-dried to 12%	5.6
Predried to 27%	9
Air-dried to 27%	25
Red maple	
Predried to 27%	12
Air-dried to 27%	25
Yellow birch	
Predried to 27%	17
Air-dried to 27%	25

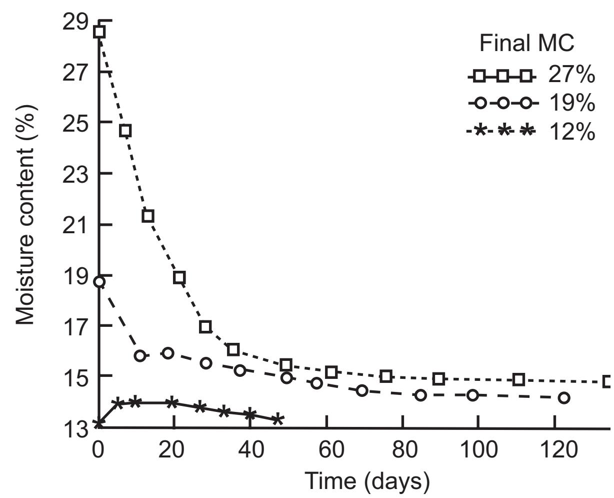

Figure 2—Curves showing moisture content loss during equilibration of sugar maple 2 by 6’s.

Table 6 shows that the amount of crook that developed during equilibration was greater when the final moisture content was 19% than when it was 12%, which is what we expected.

However, Table 6 also shows that the amount of bow and twist that developed in the boards dried to 19% moisture content was less than the amount that developed in the boards that were dried to 12%. This was an unexpected result because the boards that were kiln-dried to 19% would be expected to warp more during equilibration than those kiln-dried to 12%. This result might be explained by the stacking arrangement during equilibration. Because of limitations in the 12% EMC storage space, it was necessary to stack one

Table 3—Gross warp values for sugar maple, red maple, and yellow birch 2 by 6's during drying and equilibration to ambient EMC

Experimental variables[a]	Crook (in. (mm))	Bow (in. (mm))	Twist (in. (mm))	Cup (in. (mm))
SM KD to 27%				
BD	0.089 (2.28)	0.115 (2.39)	0.022 (0.56)	0.000 (0.00)
AD-BP	0.171 (4.34)	0.167 (4.24)	0.236 (5.99)	0.108 (2.74)
AD-AP	0.043 (1.09)	0.134 (3.40)	0.159 (4.04)	0.000 (0.00)
AE to 12%	0.128 (3.25)	0.218 (5.54)	0.230 (5.84)	0.052 (1.32)
SM KD to 19%				
BD	0.089 (2.26)	0.144 (3.66)	0.019 (0.48)	0.000 (0.00)
AD-BP	0.210 (5.33)	0.213 (5.87)	0.257 (6.53)	0.140 (3.56)
AD-AP	0.049 (1.24)	0.162 (4.11)	0.161 (4.09)	0.000 (0.00)
AE to 12%	0.095 (2.41)	0.181 (4.60)	0.173 (4.39)	0.056 (1.42)
SM KD to 12%				
BD	0.091 (2.31)	0.144 (3.66)	0.024 (0.61)	0.000 (0.00)
AD-BP	0.269 (6.83)	0.245 (6.22)	0.387 (9.83)	0.155 (3.94)
AD-AP	0.048 (1.22)	0.210 (5.33)	0.268 (6.81)	0.000 (0.00)
AE to 12%	0.078 (1.98)	0.191 (4.85)	0.184 (4.67)	0.051 (1.30)
SM PD to 27%				
BD	0.066 (1.68)	0.070 (1.78)	0.027 (0.69)	0.004 (0.10)
AD-BP	0.165 (4.19)	0.131 (3.33)	0.322 (8.18)	0.086 (2.18)
AD-AP	0.023 (0.58)	0.088 (2.24)	0.263 (6.68)	0.001 (0.03)
AE to 12%	0.133 (3.38)	0.173 (4.39)	0.484 (12.29)	0.028 (0.71)
SM AD to 27%				
BD	0.107 (2.72)	0.087 (2.21)	0.005 (0.13)	0.004 (0.10)
AD-BP	0.143 (3.63)	0.106 (2.69)	0.125 (3.18)	0.036 (0.91)
AD-AP	0.039 (0.99)	0.084 (2.13)	0.091 (2.31)	0.000 (0.00)
AE to 19%	0.098 (2.49)	0.111 (2.82)	0.140 (3.56)	0.012 (0.30)
AE to 12%	0.190 (4.83)	0.152 (3.86)	0.305 (7.75)	0.047 (1.19)
RM PD to 27%				
BD	0.060 (1.52)	0.076 (1.93)	0.019 (0.48)	0.002 (0.05)
AD-BP	0.089 (2.26)	0.093 (2.36)	0.174 (4.42)	0.032 (0.81)
AD-AP	0.005 (0.13)	0.086 (2.18)	0.126 (3.20)	0.000 (0.00)
AE to 12%	0.495 (12.57)	0.164 (4.17)	0.467 (11.86)	0.052 (1.32)
RM AD to 27%				
BD	0.069 (1.75)	0.087 (2.21)	0.023 (0.58)	0.001 (0.03)
AD-BP	0.128 (3.25)	0.123 (3.12)	0.302 (7.67)	0.047 (1.19)
AD-AP	0.047 (1.19)	0.115 (2.92)	0.206 (5.23)	0.001 (0.03)
AE to 19%	0.110 (2.79)	0.123 (3.12)	0.288 (7.32)	0.013 (0.33)
AE to 12%	0.122 (3.10)	0.115 (2.92)	0.314 (7.98)	0.027 (0.69)
YB PD to 27%				
BD	0.091 (2.31)	0.064 (1.63)	0.026 (0.66)	0.000 (0.00)
AD-BP	0.122 (3.10)	0.069 (1.75)	0.163 (4.14)	0.035 (0.89)
AD-AP	0.013 (0.33)	0.065 (1.65)	0.090 (2.29)	0.000 (0.00)
AE to 12%	0.167 (4.24)	0.144 (3.66)	0.302 (7.67)	0.033 (0.84)
YB AD to 27%				
BD	0.113 (2.87)	0.094 (2.39)	0.030 (0.76)	0.003 (0.08)
AD-BP	0.183 (4.65)	0.142 (3.61)	0.307 (7.80)	0.054 (1.37)
AD-AP	0.028 (0.71)	0.107 (2.72)	0.214 (5.44)	0.000 (0.00)
AE to 12%	0.123 (3.12)	0.145 (3.68)	0.298 (7.57)	0.009 (0.23)

[a]SM, sugar maple; RM, red maple; YB, yellow birch; KD, kiln-dried; PD, predried; AD, air-dried; BD, before drying; AD-BP, after drying, before planing; AD-AP, after drying, after planing; AE, after equilibration.

Table 4—Absolute values of net warp for sugar maple, red maple, and yellow birch 2 by 6's during drying and equilibration to ambient EMC

Experimental variables[a]	Crook (in. (mm))	Bow (in. (mm))	Twist (in. (mm))	Cup (in. (mm))
SM KD to 27%				
AD-BP	0.088(2.24)	0.106(2.69)	0.219(5.56)	0.108(2.74)
AE to 12%	0.088(2.24)	0.095(2.41)	0.095(2.41)	0.052(1.32)
SM KD to 19%				
AD-BP	0.124(3.15)	0.135(3.43)	0.241(6.12)	0.140(3.56)
AE to 12%	0.050(1.27)	0.045(1.14)	0.066(1.68)	0.056(1.42)
SM KD to 12%				
AD-BP	0.183(4.65)	0.158(4.01)	0.365(9.27)	0.155(3.94)
AE to 12%	0.043(1.09)	0.066(1.68)	0.100(2.54)	0.051(1.30)
SM PD to 27%				
AD-BP	0.108(2.74)	0.078(1.98)	0.291(7.39)	0.082(2.08)
AE to 12%	0.109(2.77)	0.093(2.36)	0.224(5.69)	0.028(.071)
SM AD to 27%				
AD-BP	0.054(1.37)	0.060(1.52)	0.122(3.01)	0.034(0.86)
AE to 19%	0.060(1.52)	0.055(1.40)	0.068(1.73)	0.013(2.06)
AE to 12%	0.151(3.84)	0.093(2.36)	0.218(5.54)	0.046(1.17)
RM PD to 27%				
AD-BP	0.038(0.97)	0.044(1.12)	0.156(3.96)	0.032(0.81)
AE to 12%	0.450(11.43)	0.110(2.79)	0.341(8.66)	0.052(1.32)
RM AD to 27%				
AD-BP	0.066(1.68)	0.052(1.32)	0.283(7.18)	0.047(1.19)
AE to 19%	0.064(1.63)	0.070(1.78)	0.119(3.02)	0.013(0.33)
AE to 12%	0.076(1.93)	0.067(1.70)	0.140(3.56)	0.026(0.66)
YB PD to 27%				
AD-BP	0.042(1.07)	0.034(0.89)	0.140(3.56)	0.035(0.89)
AE to 12%	0.167(4.24)	0.097(2.46)	0.217(5.51)	0.033(0.84)
YB AD to 27%				
AD-BP	0.085(2.16)	0.076(1.93)	0.272(6.91)	0.051(1.30)
AE to 12%	0.095(2.41)	0.072(1.83)	0.090(2.29)	0.009(0.23)

[a]SM, sugar maple; RM, red maple; YB, yellow birch; KD, kiln-dried; PD, predried; AD, air-dried; AD-BP, after drying, before planing; AE, after equilibration.

Table 5—Net warp occurring during kiln drying of sugar maple 2 by 6's

Final moisture content (%)	Crook (in. (mm))	Bow (in. (mm))	Twist (in. (mm))	Cup (in. (mm))
12	0.183 (4.65)	0.158 (4.01)	0.365 (9.27)	0.155 (3.94)
19	0.124 (3.15)	0.135 (3.43)	0.241 (6.12)	0.140 (3.56)
27	0.088 (2.24)	0.106 (2.69)	0.218 (5.54)	0.108 (2.74)

Table 6—Net warp occurring during post-kiln equilibration of sugar maple 2 by 6's

Final moisture content (%)	Crook (in. (mm))	Bow (in. (mm))	Twist (in. (mm))	Cup (in. (mm))
12	0.0421 (1.07)	0.0664 (1.69)	0.0999 (2.54)	0.0507 (1.29)
19	0.0496 (1.26)	0.0453 (1.15)	0.0652 (1.66)	0.0557 (1.41)
27	0.0878 (2.23)	0.0952 (2.42)	0.0952 (2.42)	0.0523 (1.33)

group on top of the other. The boards kiln-dried to 27% were stacked on top of those kiln-dried to 19%, which resulted in more weight restraint on the 19% boards during equilibration. This restraint apparently reduced the amount of bow and twist that developed during equilibration. The boards kiln-dried to 12% did not have anything stacked on top during equilibration. The difference in response between the crook that developed in the 19% boards (which was more than that of the 12% boards) and the bow and twist that developed in the same boards is in accord with the observation that Koch (1974) made on southern pine 2 by 4's. His research showed that top restraint was effective in reducing bow and twist but was not effective in reducing crook.

Table 7 shows the effect of drying method on warp in sugar maple. There are few clear patterns that suggest that drying method affects the amount of warp that develops during drying or during equilibration. Bow and cup may be greater in kiln drying than in pre- or air drying, and twist may be greater in predrying than in air or kiln drying. However, it is difficult to rationalize reasons for these observations.

Table 8 shows the effect of species on the amount of warp occurring during drying and during equilibration. As was the case with the drying method comparisons, there does not appear to be any general pattern to suggest any species included in this study warps more than any other.

Table 7—Effect of drying method on warp in sugar maple 2 by 6's dried to 27% moisture content

Experimental variables[a]	Crook (in. (mm))	Bow (in. (mm))	Twist (in. (mm))	Cup (in. (mm))
		Gross warp		
AD-BP				
Kiln-dried	0.171 (4.34)	0.167 (4.24)	0.236 (5.99)	0.108 (2.74)
Predried	0.165 (4.19)	0.131 (3.33)	0.322 (8.18)	0.086 (2.18)
Air-dried	0.143 (3.63)	0.106 (2.69)	0.125 (3.18)	0.036 (0.91)
Equilibration to 12% (AE)				
Kiln-dried	0.127 (3.23)	0.218 (5.54)	0.230 (5.84)	0.052 (1.32)
Predried	0.132 (3.35)	0.173 (4.39)	0.484 (12.29)	0.028 (0.71)
Air-dried	0.190 (4.83)	0.152 (3.86)	0.305 (7.75)	0.047 (1.19)
		Net warp		
AD-BP				
Kiln-dried	0.088 (2.24)	0.106 (2.69)	0.219 (5.56)	0.108 (2.74)
Predried	0.108 (2.74)	0.078 (1.98)	0.291 (7.39)	0.082 (2.08)
Air-dried	0.054 (1.37)	0.060 (1.52)	0.122 (3.10)	0.034 (0.86)
Equilibration to 12% (AE)				
Kiln-dried	0.088 (2.24)	0.095 (2.41)	0.09 (2.41)	0.052 (1.32)
Pre-dried	0.109 (2.77)	0.093 (2.36)	0.224 (5.69)	0.028 (0.71)
Air-dried	0.151 (3.84)	0.093 (2.36)	0.218 (5.54)	0.047 (1.19)

[a]AD-BP, after drying, before planing; AE, after equilibration.

Grade Loss from Warp

To get an idea of how serious the observed warp was, we evaluated it by southern pine grading rules (SPIB 1994). Whether or not grade warp limits for hardwoods would be the same as for softwoods is unknown at this point. The limits for warp in various structural grades of 2 by 6's are shown in Table 9. Table 10 shows the percentage of boards that meet Number 2 grade warp requirements immediately after drying and surfacing and also after equilibration. The percentages are shown according to type of warp, drying method, species, and final target moisture content (in the case

Table 8—Effect of species on warp in 2 by 6's

Experimental variables[a]	Crook (in. (mm))	Bow (in. (mm))	Twist (in. (mm))	Cup (in. (mm))
		Gross warp		
AD-BP				
SM-PD	0.165 (4.19)	0.131 (3.33)	0.322 (8.18)	0.086 (2.18)
RM-PD	0.089 (2.26)	0.093 (2.36)	0.174 (4.42)	0.032 (0.81)
YB-PD	0.121 3.07)	0.069 (1.75)	0.163 (4.14)	0.035 (0.89)
SM-AD	0.143 (3.63)	0.106 (2.69)	0.125 (3.18)	0.036 (0.91)
RM-AD	0.128 (3.25)	0.123 (3.12)	0.302 (7.67)	0.047 (1.19)
YB-AD	0.183 (4.65)	0.142 (3.61)	0.307 (7.80)	0.054 (1.37)
Equilibration to 12% (AE)				
SM-PD	0.133 (3.38)	0.173 (4.39)	0.484 (12.29)	0.028 (0.71)
RM-PD	0.495 (12.57)	0.164 (4.17)	0.467 (11.86)	0.052 (1.32)
YB-PD	0.167 (4.24)	0.144 (3.66)	0.302 (7.67)	0.033 (0.84)
SM-AD	0.190 (4.83)	0.152 (3.86)	0.305 (7.75)	0.047 (1.19)
RM-AD	0.122 (3.10)	0.115 (2.92)	0.314 (7.98)	0.027 (0.69)
YB-AD	0.123 (3.12)	0.145 (3.68)	0.298 (7.57)	0.009 (0.23)
		Net warp		
AD-BP				
SM-PD	0.108 (2.74)	0.078 (1.98)	0.291 (7.39)	0.082 (2.08)
RM-PD	0.039 (0.99)	0.044 (1.12)	0.156 (3.96)	0.032 (0.81)
YB-PD	0.042 (1.07)	0.034 (0.86)	0.140 (3.56)	0.035 (0.89)
SM-AD	0.054 (1.37)	0.060 (1.52)	0.122 (3.10)	0.034 (0.86)
RM-AD	0.066 (1.68)	0.053 (1.35)	0.283 (7.19)	0.047 (1.19)
YB-AD	0.085 (2.16)	0.076 (1.93)	0.272 (6.91)	0.051 (1.30)
Equilibration to 12% (AE)				
SM-PD	0.109 (2.77)	0.093 (2.36)	0.224 (5.69)	0.028 (0.71)
RM-PD	0.450 (11.43)	0.110 (2.79)	0.341 (8.66)	0.052 (1.32)
YB-PD	0.167 (4.24)	0.097(2.46)	0.217 (5.51)	0.033 (0.84)
SM-AD	0.151 (3.84)	0.093(2.36)	0.218 (5.54)	0.046 (1.17)
RM-AD	.076 (1.93)	0.067 (1.70)	0.140 (3.56)	0.026 (0.66)
YB-AD	0.095 (2.41)	0.072 (1.83)	0.090 (2.29)	0.009 (0.23)

[a]AD-BP, after drying, before planing; AE, after equilibration; SM, sugar maple; RM, red maple; YB, yellow birch; PD, predried; AD, air-dried.

Table 9—Warp limits for 8-ft- (2.4-m-) long southern pine structural 2 by 6's (SPIB 1994)

Grade	Crook (in. (mm))	Bow (in. (mm))	Twist (in. (mm))	Cup (in. (mm))
Select Structural	0.250 (6.4)	0.500 (12.7)	0.563 (14.3)	0.0625 (1.6)
1	0.250 (6.4)	0.500 (12.7)	0.563 (14.3)	0.0625 (1.6)
2	0.313 (2.5)	0.750 (19.1)	0.750 (19.1)	0.0625 (1.6)
3	0.500 (12.7)	1.000 (25.4)	1.125 (28.6)	0.1250 (3.2)

of kiln drying). Although commercial planing equipment and methods probably differ from our laboratory capabilities, the data show that the planing operation is capable of greatly reducing downgrade from warp that occurs during drying. Surfacing out warp to meet grade requirements requires larger target dimensions for sawn lumber, which reduces yield and wastes resource. However, considering the poor use potential of this type of material, reduced yield may be justifiable. The results in Table 10 are somewhat varied. In all cases, the percentage of boards meeting grade warp requirements after drying and planing was high, from 97% to 100%. In many cases, the percentage was still high after equilibrating to 12% moisture content. The worst case was red maple equilibrated to 12% after predrying to 27% moisture content. For this group, the percentage of boards meeting grade warp requirements was only 38.6%, and there is no apparent reason for this outlying result. There is concern that cup might be a problem in equilibration. For kiln-dried sugar maple, the percentage of boards that met grade warp requirements based on cup dropped into the 80% range during equilibration to 12% moisture content. The percentage of red maple boards predried to 27% moisture content that met grade warp requirements after equilibration also dropped into the 80% range.

Currently, most structural lumber is kiln-dried to 15% to 19% moisture content. Because of post-kiln drying to ambient equilibrium conditions of 12% moisture content or below and the potential danger of warp during that drying, some are suggesting that structural lumber be dried closer to these ambient EMCs (Koch 1971, Markstrom and others 1984). The concern with this approach is that warp and thus grade loss during kiln drying may be increased, and kiln residence time and thus required kiln capacity will certainly be increased. At the other extreme, it would be desirable to dry to final moisture contents higher than 19% to reduce required kiln capacity and residence time, even though the danger of post-kiln drying warp exists. This study provides data to help make a decision on optimum final moisture content of

Table 10—Percentage of boards that meet southern pine grade requirements for warp in Number 2 grade (Forest Products Laboratory 1991)

	Percentage of boards			
Experimental variables[a]	Crook	Bow	Twist	Cup
SM Kiln-dried to 27%				
AD-AP	100	100	100	100
AE to 12%	97.3	100	100	82.9
SM Kiln-dried to 19%				
AD-AP	100	100	100	100
AE to 12%	99.1	100	100	84.7
SM Kiln-dried to 12%				
AD-AP	100	99.1	97.3	100
AE to 12%	98.2	100	100	85.6
SM Predried to 27%				
AD-AP	100	100	100	100
AE to 12%	95.1	99.0	87.3	100
SM Air-dried to 27%				
AD-AP	100	100	100	100
AE to 19%	100	100	100	100
AE to 12%	86.1	100	96.0	92.1
RM Predried to 27%				
AD-AP	100	100	100	100
AE to 12%	38.6	100	89.1	85.1
RM Air-dried to 27%				
AD-AP	100	99.0	99.0	100
AE to 19%	98.0	100	93.1	100
AE to 12%	96.0	100.	94.1	100
YB Predried to 27%				
AD-AP	100	100	100	100
AE to 12%	88.1	100	100	100
YB Air-dried to 27%				
AD-AP	100	99.0	100	100
AE to 12%	99.0	100	97.0	100

[a]SM, sugar maple; RM, red maple; YB, yellow birch; AD-AP, after drying, after planing; AE, after equilibration.

hardwoods for structural purposes. However, the results suggest that even though increased warp develops when final moisture content immediately after drying is reduced to 12%, it probably can be surfaced out in most planing operations. But because the additional warp that develops during equilibration of sugar maple kiln-dried to only 27% may not reduce grade appreciably, it may also be appropriate to rethink and further investigate the idea of increasing final moisture content to some level above the common 15% to 19%. However, before a higher final moisture content could be recommended, the effects of post-kiln drying shrinkage in terms of variable size and fastener integrity would have to be investigated.

Conclusions and Recommendations

This study confirms the expected result that the amount of warp that develops in kiln drying hard maple 2 by 6's increases as the final average moisture content decreases. The results also show that if this lumber is kiln-dried to a final moisture content higher than 15% to 19%, warp will increase but grade loss (assuming softwood grade warp limits would also apply to hardwoods) may not seriously increase from the warp that occurs as moisture content decreases to typical ambient levels of about 12%. Similarly, in most cases, sugar maple, red maple, and yellow birch 2 by 6's air- or predried to 27% moisture content did not suffer much grade loss from warp during equilibration. The results of one laboratory study are not sufficient to recommend higher final moisture contents in commercial applications, but they do suggest that for sugar maple, red maple, and yellow birch, it may be possible to increase kiln efficiency for structural applications by raising final moisture content above the 15% to 19% range if shrinkage and fastener integrity are not problems. We recommend that further research or field tests be conducted to confirm or disprove the results of this study.

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