THE INFLUENCE OF DRYING CONDITIONS AND OTHER FACTORS ON TWIST AND TORQUE IN *PINUS RADIATA* STUDS

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ABSTRACT

Pinus radiata studs of cross section 4 × 1½ inch, sawn to enclose the pith, were dried in conditions of high and low temperatures, high and low air velocities, with and without presteaming, and with and without mechanical restraint. The resultant twist and torque values were measured and it was found that torque developed during drying was negatively correlated with drying rate. The results are interpreted in terms of the elastic-plastic properties of wood during drying. Torque values were used to calculate the equivalent loads required to restrain packs of this timber from twisting during drying and these compared well with optimum loads derived empirically in commercial trials.

Additional Keywords: Kiln drying, seasoning, steaming, high temperature drying, drying under restraint, degrade, warp.

INTRODUCTION

To meet an ever-growing demand for dried softwood framing timber, two major research developments in drying techniques stand out in recent years. These are the use of elevated drying temperatures, i.e. in excess of 100 C, and the utilization of distortion-prone juvenile core material cut from early thinnings and veneer cores. Distortion in this material is mainly twist, and Balodis (1971) demonstrated on four major commercial softwood species from Queensland (Australia) plantations that the angle of twist increases with increasing angle of spiral grain and decreases with increasing distance of the board from the pith.

Production of dry straight studs has been described in detail for a number of softwood species (Koch 1971; Mackay and Rumball 1971; and Christensen and Gough in preparation). In brief, these processes consisted of kiln-drying the timber at a dry bulb temperature of 115 C and a depression of 44 C with an air velocity through the stacks of around 1,000 ft per min. The timber used in the first-mentioned study was held in mechanical restraint clamped in aluminium frames and in the other two under reinforced concrete slabs laid over the top of the stacks. Restraint was maintained throughout the whole of the drying cycle including final steaming for stress relieving and the cooling down period at the end. There is no indication in the former case of the forces applied by the frame to the timber; in the second case the top loadings investigated in detail ranged up to 220 lb ft^{-2} (1078 kg m^{-2}).

It is unlikely that the frames or slabs as used by these authors will be acceptable to industry in the long term as mechanisms for applying restraint. However, it is difficult to envisage designs of alternative equipment without knowing certain facts about the twisting process in the drying of studs. This study was designed to follow the development of twist in individual studs during the drying process, to evaluate the forces required to hold them straight or to straighten them, and to investigate the interaction of kiln-drying conditions on these values.

EXPERIMENTAL AND RESULTS

Butt logs from a large number of 24-year-old plantation grown *Pinus radiata* thinnings were sawn to yield 9-ft × 4- × 1½-inch studs cut to symmetrically enclose the pith. These were each sawn to give 4-ft × 4- × 1½-inch

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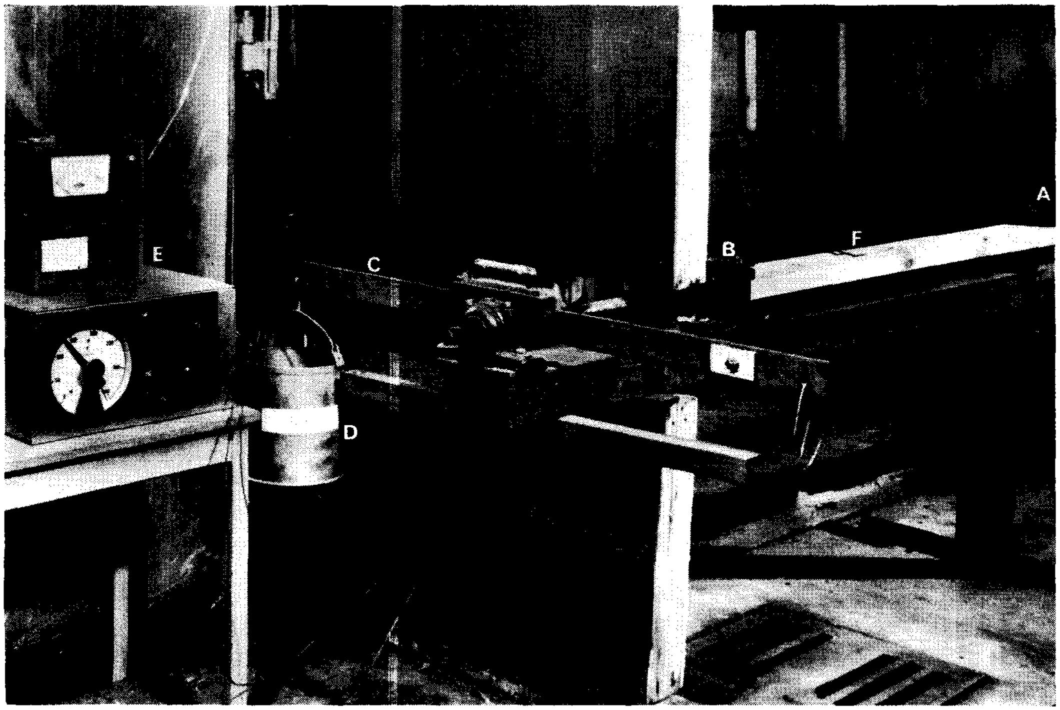

FIG. 1. Drying jig for single test samples shown with kiln wall cut away and air flow baffles removed. Each 4-ft length was clamped firmly in a horizontal position at one end *A* and was free to twist at the other end *B*. A cross-bar *C* pivoted about the extension rod from *B* allowed accurate measurement of twist angle changes to be made and served to hold adjustable weights *D*. Temperatures and moisture contents were monitored *E* through copper-constantan thermocouples inserted at the midpoint *F*.

test samples and three green moisture content sections. In most instances experiments were designed to make use of the end-matching of the pairs of 4-ft samples. While there was slight variation in the relative amounts of heartwood and sapwood between trees, this was insignificant or not apparent between any two end-matching samples. The difference in green moisture contents between matching pairs was small ($\leq 5\%$ MC), but for trees the range of moisture content was 80–120%. This was clearly a function of the relative amounts of heartwood and sapwood.

Test samples were kiln-dried individually in a system (Fig. 1) designed so that during drying they could be either restrained from twisting or free to twist. If they were free to twist, then the total angle of twist between the ends of the sample was measurable by the angle to the horizontal of the bar on the free end. At either end of this bar, weight was suspended to reestablish the original position and the restoring torque (simply called torque) calculated as the product of this mass and the distance from the point of pivot of the bar. These measurements were made at regular intervals throughout the drying period.

To restrain a sample from twisting during drying, the bar was clamped in a horizontal position and at intervals released for a few seconds to allow angle of free twist and torque to be determined and then reclamped.

The standard high-temperature schedule used was a constant dry bulb temperature of 115 C with a wet bulb depression of 44 C. Air flow, measured with a Hastings Raydist Meter, across the wide faces of the samples

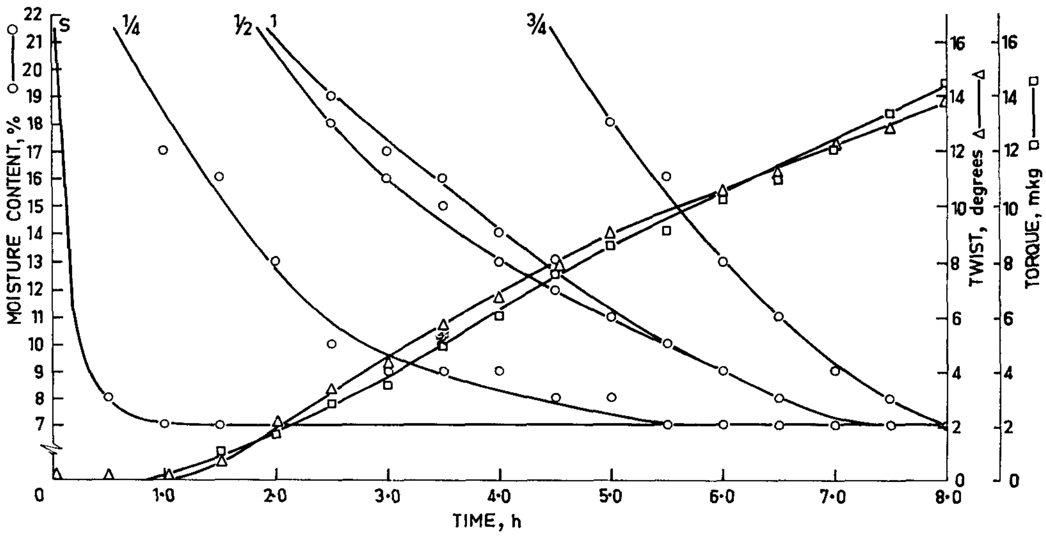

FIG. 2. Moisture contents (%) on the surfaces and at depths of ¼, ½, ¾ and 1 inch, twist (degrees), and torque (m kg) measured over the first 8 hr of unrestrained high-temperature drying of test sample no. 1B.

was approximately 1,200 ft per min. To test the effects of some drying parameters, the schedule and air velocity were independently changed to 82 C dry bulb and 22 C depression, and 450 ft per min, respectively. Presteaming where required was done by maintaining saturated conditions of 100 C in the kiln for 2 hr prior to commencement of drying.

In the center of each test sample, two copper-constantan thermocouples were inserted side-by-side to a depth of ⅞ inch at 1¼-inch spacing as shown in Fig. 1. A resistance moisture meter read the apparent moisture content between the copper electrodes, and the thermocouples gave the temperature reading at the point of measurement. True moisture contents could then be determined from a table experimentally derived to correct for the effect of temperature and species. The upper and lower limits of corrected moisture contents using this system were 18% and 7%, respectively. In some samples five pairs of thermocouples were inserted to varying depths near midspan to determine a moisture content profile during the drying process.

Since the total amount of twist occurring in any sample is a function of the angle of spiral grain, then the torque developed in any sample is not comparable with that in a sample prepared from another tree. To overcome this for comparative purposes, torque was calculated and expressed per unit degree of twist at that time.

Simultaneous measurement of moisture content, twist angle, and torque

Four test samples were dried at high temperature without restraint, and five thermocouple pairs were inserted on the drying surface, and at depths of ¼, ½, ¾ and 1 inch. Thus the ½- and 1-inch thermocouples were each ½ inch from one of the two drying faces. In Fig. 2 is shown a drying pattern of one sample typical of all four, and the development of twist and torque. Moisture content readings are relevant only below fiber saturation point since only then can shrinkage and distortion occur.

Effects of drying temperature and presteaming

Twelve matching pairs of samples were prepared to examine these effects. An in-

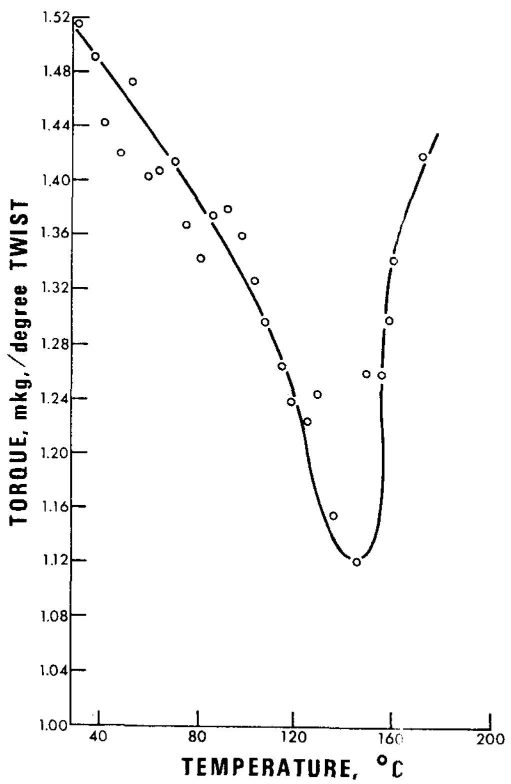

FIG. 3. Effect of increasing temperature on torque (m kg) per degree twist developed in a dry test sample no. 33B.

complete block design was used whereby each pair of treatments occurred together once in the same complete stud and there were six replications of each treatment. All samples were unrestrained. The effects due to temperature and presteaming given in Table 1 were both significant at the 1% level. Thus most torque was developed (and most restoring force required to straighten) in samples dried at low temperature and without presteaming. Conversely, use of high drying temperature and presteaming resulted in development of least torque.

Torque developed in restrained and unrestrained samples

From each of three matched pairs, one sample was high-temperature-dried in restraint and the other without restraint, to

TABLE 1. *The effect of temperature and presteaming on torque (m kg) per degree of twist. Treatment means adjusted for stud differences*

Treatment	Drying Conditions	
	High Temperature	Low Temperature
	m kg per degree	
Presteamed	0.824	1.121
Not presteamed	1.112	1.343

a core moisture content of 12%. The results in Table 2 show that while restraint reduced the angle of twist considerably, there was a corresponding reduction in the torque such that on a torque per degree basis there was no significant difference within the matched pairs. Similar results between the two groups were obtained whether or not presteaming was used.

Effects of drying rate

Matched samples were high-temperature-dried without restraint to a core moisture content of 12% in the kiln at the two air velocities of 1,200 or 450 fpm and drying rates, twist, and torque determined. Results in Table 3 show that while the slower drying rate caused no more twist at the same moisture content, the torque developed was consistently greater.

Effects of temperature

Six boards previously high-temperature-dried without presteaming to less than 4% moisture content were randomly selected, set up in the jig, and twist and torque determined at intervals while the kiln temperature was raised from ambient temperature

TABLE 2. *Torque and twist developed in three pairs of restrained and unrestrained matched samples dried to 12% moisture content at high temperature and air velocity*

Stud	Treatment	Twist (degrees)	Torque (m kg)	Torque (m kg) per degree
12	Restrained	3.0	2.940	0.980
	Unrestrained	8.5	7.990	0.940
14	Restrained	2.0	2.670	1.335
	Unrestrained	6.0	8.880	1.380
19	Restrained	2.5	3.463	1.385
	Unrestrained	7.5	9.938	1.325

TABLE 3. *Effect of air velocity on torque and twist developed in three pairs of unrestrained matched samples dried at high temperature to 12% moisture content*

Stud	Air velocity (fpm)	Drying time to 12% MC (h)	Twist (degrees)	Torque (m kg)
11	450	13.5	9.0	8.775
	1200	9.5	9.5	5.700
24	450	14.0	13.0	12.410
	1200	8.0	12.0	7.224
26	450	15.5	10.5	11.445
	1200	10.0	11.0	7.260

(around 27 C) to the highest attainable (160 C) at minimum humidity. Since the samples were at very low moisture contents at the beginning of the run, there was little increase in twist angle, viz ≤ 1 degree. A typical result is shown in Fig. 3: torque declined steadily with temperature increase to form a definite minimum, in this instance the minimum was at 143 C. The other samples gave similar results with minima between 127 C and 146 C.

Effects of cycling between 5% and 15% moisture content

Twelve samples that had previously been dried in restraint at high temperature without presteaming were brought to equilibrium conditions of 5% and 15% EMC alternately, without restraint. These were held at each condition five times and each time twist and torque were measured. All samples behaved similarly and Table 4 shows typical results. Variation in angle of twist and torque for each sample was small at the two equilibrium conditions with no consistent trend.

TABLE 5. *Dead loads (kg) per meter of stack width to be applied at each end of a stack of 4- × 1½-inch Radiata pine studs to restrain them from twisting during drying. The values were derived from torque measurements (m kg) on six 4-ft × 4- × 1½-inch test samples dried under restraint*

Stud	Treatment	Torque (m kg)	Top load (kg) per meter of stack width
12	Not presteamed	2.940	588
14	do.	2.670	534
19	do.	3.463	693
27	Presteamed	2.175	435
29	do.	1.403	281
31	do.	3.185	637

TABLE 4. *Twist (degrees) and torque (m kg) developed in four high-temperature-dried test samples repeatedly cycled between equilibrium conditions of 5% and 15% moisture content*

	1A		3A		4B		66B	
EMC(%)	TWIST	TORQUE	TWIST	TORQUE	TWIST	TORQUE	TWIST	TORQUE
5	14.0	14.98	14.5	16.02	16.5	21.00	15.5	15.16
15	6.5	7.22	5.0	5.27	7.0	8.99	7.0	6.41
5	16.0	18.00	15.0	16.65	16.0	19.90	15.5	14.46
15	7.5	8.03	6.0	6.52	7.0	8.28	7.5	7.00
5	14.5	15.17	15.5	16.12	16.0	19.79	15.0	14.49
15	7.0	6.76	5.0	5.18	7.0	7.63	7.5	7.31
5	14.5	15.08	14.0	14.60	16.5	21.19	14.5	14.01
15	6.5	7.06	6.0	6.55	6.5	7.75	6.5	6.11
5	14.5	16.43	15.0	15.45	16.0	19.55	15.5	15.27
15	6.5	7.22	6.5	7.09	7.0	8.48	6.5	6.28

DISCUSSION

One general conclusion of some interest is that the magnitude of torque or of torsion modulus varied with the drying rate. This was evident in two cases. Torque was greater in samples dried in a low air velocity than those dried at equal temperature in a high air velocity (Table 3). Likewise it was greater in samples dried at low temperature than at high temperature, other drying parameters being equal (Table 1). However, the two cases should be considered quite separately.

At the same drying temperature, samples dried relatively slowly probably developed a greater plastic set than matching material dried faster. That is, while in both cases the timber twisted during drying because of the shrinkage of spirally aligned wood, more plastic, at the expense of elastic, deformation occurred during the longer drying period and conversely relatively more elastic deformation occurred in matching material dried in a shorter drying period.

These explanations for the reported variation of torsion moduli without drying conditions contradict conventional creep data where deformation is related to total moisture content change rather than to the means by which the changes are brought about. Different drying rates, whether they be a result of air velocity or temperature levels, might be expected to lead to development of moisture and stress gradients of varying degrees and these in turn might be expected to give differences in torsion moduli. For example, considering the two drying temperatures tested, it could be argued that the lower modulus in a board dried at high temperature was a result of a low-stress condition in the case relative to the core, i.e. the case was in compression and the board could be described as casehardened. Stress gradients were not measured after drying; thus it is difficult to resolve this point. However, boards that were cycled between 5% and 15% moisture content would have been expected to undergo a certain amount of stress relieving each time they were put in the higher humidity until ultimately the stresses would be neutralized. The result of this treatment, had stress gradients been present, should have been to increase twist as elastic stresses were relieved. As Table 4 shows, no trend of increased twist and torque was apparent in successive cycles.

In comparing the effects of high and low drying temperatures, the probable influence of thermal softening is of significance. Thermal softening or plasticizing by heat at the high temperature used acted in addition to the time-dependent elastic-plastic deformations so that torque was lower in high-temperature-dried samples due to thermal softening and low plastic deformation, and higher in matching low-temperature-dried samples with less thermal softening and more plastic deformation.

Presteaming prior to the onset of drying had no effect on the angle of twist. Torque, however, was reduced significantly in both restrained and unrestrained samples. In the former case, the influence of presteaming at 100 C was to plasticize the wood, make it more malleable, and allow the restraining force to have more effect. Similarly in unrestrained samples, the plasticized condition was established in presteaming and was maintained throughout the drying period. In each case the torque developed at any given time was less than in the respective untreated samples. Thus the use of presteaming in either of the commercial applications listed earlier could be expected to raise the yield of straight boards, as was demonstrated experimentally by Mackay and Rumball (1972).

Samples held in restraint throughout the drying process took on a plastic set such that the twist angle and torque were proportionally reduced. It is likely that plastic flow of lignin mainly in the interfiber bonds but also in cell walls allowed this to occur. It has been a feature of studs dried at high temperature under restraint that they retain their straightness permanently and move only in response to changes in equilibrium moisture conditions. That is they do not revert to a twisted condition, (Koch 1971; Mackay and Rumball 1971). This was further demonstrated in this study where the cycling of samples between 5% and 15% moisture content had little effect on twist or torque at either equilibrium condition.

That twist began within the first hour and a half of drying is of interest since by that time only the case was below fiber saturation point and therefore shrinking. This and the fact that twist angle and hence torque were then linearly related to drying time means that the wet core had no restraining effect on the sample as a whole. This is no doubt due to the superior strength properties of dry wood compared to green, and to the fact that in torsion the greater force is exerted by the outside furthest from the axis.

Chow and Pickles (1971) investigated thermal softening of wood and bark specimens of several species at different moisture contents. Their results indicate that the maximum rate of softening for oven-dry wood occurred around 380 C, but in the presence of moisture another softening peak appeared below 180 C. The temperatures of minimum torque developed in the present study, i.e. 127–143 C, were lower than the softening points found by Chow and Pickles particularly when the low moisture contents of the studs ($\leq 4\%$ MC) are considered. The shape of the softening rate curves for oven-dry specimens, and those given by Goring (1963) in a similar study with isolated lignin, hemicellulose, and cellulose are, however, similar to the curve for torque versus temperature. It is likely therefore that the high temperatures used in these experiments and those used in the commercial tests listed played a large role in overcoming the distortion due to anisotropic shrinkage in restrained samples.

The torque values obtained from samples dried in restraint are those most relevant to the commercial practice of high-temperature-drying under concrete blocks or in frames as described. To convert these values to dead loads applied over an 8-ft-length, certain assumptions have been made. It is assumed that twist is uniform along the total length. This was so in the experimental samples tested, no doubt due to the fact that they were sawn so that the pith was symmetrically enclosed. In this situation the most effective means of applying a load to a stack to prevent twist is to distribute it equally at each end. The only reason to have extra load between the ends would be if boards in the stack were of unequal length or if intermediate sections of boards have additional tendencies to twist. If the board and stack dimensions are known and the magnitude of torque that can develop in that board cross section is approximated, then it is possible to calculate the required loads.

If w is the load applied to one stud, then w/2 acts at each end. Total restraining torque for a given stud,

$$T = \frac{wb}{2}, \qquad (1)$$

where b is stud width and

$$w = \frac{2T}{b}. \qquad (2)$$

If n is the number of such studs across a stack and the total load is W, then,

$$W = \frac{2nT}{b}. \qquad (3)$$

If B is the width of the stack and all the studs are lying edge-to-edge, then,

$$n = \frac{B}{b}, \qquad (4)$$

and,

$$W = \frac{2BT}{b^2}. \qquad (5)$$

If the stud width is 4 inches (10 cm) as in this study and torque is expressed in m kg units, then, $W/B = 2\ T\ 10^2$ kg per meter of stack width.

Using the data from restrained samples in the experiments described, the equivalent loads can now be determined, Table 5. When the top loads used in the commercial trials with 4 × 1½ inch radiata pine described by Mackay and Rumball (1971) are recalculated on a stack width basis, the recommended load becomes 1308 kg at each end. This is higher than the values determined here; however, the tests carried out in this study were done with single samples in ideal conditions and the figures thus obtained should be recognized as being minimal only.

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