Ann Sci For (1996) 53, 1177-1188

Original article

The influence of wood quality on lumber drying distortion*

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(Received 4 July 1995; accepted 11 March 1996)

Summary – Commercial experience with the sawing of logs from fast-grown plantations has shown that there can be significant drying distortion associated with the presence of juvenile wood. In New Zealand this is a growing concern due to the reduction of rotation ages for radiata pine (*Pinus radiata* D Don) to around 25–30 years. The purpose of this analysis was to use the results of sawing studies to identify some of the major factors affecting distortion of the final product (structural lumber in this case) and test the feasibility of modeling the relationships. Analyses of some 9 000 individual boards (100 x 40 and 100 x 50 mm) from 1 000 logs indicated the need to take into account a range of factors relating to the raw material (logs), secondary processing technology (sawing pattern, drying method and the influence of planing), product (lumber dimensions) and standards (grading rules). The strong propensity for lumber from small diameter and physiologically young logs to degrade was confirmed and over 90% of the problem was related to twist rather than crook or bow. In the worst cases (small juvenile logs, low temperature drying, no planing) up to 80% of the boards were categorized as 'rejects'. At the other extreme, large diameter mature logs dried according to recommended practices and those that were machined to final size showed around a 5% rate of rejection. Diameter was shown to be the most influential log property. Spiral grain was also important due to its influence on twist during drying; it is greatest in juvenile wood which forms a greater proportion in small diameter logs. The analyses showed that both diameter and spiral grain are related to twist. Unfortunately, spiral grain is a little known feature of plantation pines, and is only now gaining the research attention it deserves. The results presented here indicate that log diameter of radiata pine is a good indicator of the propensity for lumber to twist during drying. Since this can be predicted using forest management models, it is proposed to extend the capability of predictive models by modifying them to assess the yields of dried, finished products.

wood quality / juvenile wood / drying degrade / twist / modeling

Résumé – L'effet de propriétés du bois sur les défauts du séchage. *L'expérience industrielle récente de débit de grumes, provenant de plantations à croissance rapide, montre qu'un degré significatif de déclassement peut survenir au séchage. Ce déclassement serait associé à la présence de bois juvénile. Ce problème est préoccupant en Nouvelle-Zélande étant donné que la révolution en plantations de pin radiata (*Pinus radiata *D Don) a été réduite à environ 25–30 ans. La présente étude vise à utiliser les résultats d'études de séchage pour identifier les causes majeures de gauchissement*

*Paper presented at the IUFRO Workshop S5.01.04, Hook, Sweden, 13–17 June 1994.

dans des produits finaux (dans le cas présent, des membrures structurales) ainsi qu'à tester la faisabilité de la modélisation des causes et effets. L'analyse de quelque 9 000 débits (100 x 40 et 100 x 50 mm) provenant de 1 000 grumes indique la nécessité de considérer une série de facteurs reliés tant à la matière première (grumes) qu'aux procédés de transformation secondaires (schémas de débitage, méthode de séchage et influence du rabotage), aux produits (dimentions des débits) et aux standards (règles de classification). Une forte tendance au déclassement a été confirmée chez les débits provenant de grumes de faible diamètre et physiologiquement juvéniles et plus de 90 % des problèmes étaient reliés au gauchissement en torsion plutôt qu'au gauchissement de rive ou à plat. Dans les pires cas (grumes juvéniles de faible dimention, séchage à basse température, pas de rabotage) près de 80 % des débits entraient dans la catégorie des « rejets ». À l'autre extrême, les débits provenant de grumes matures et de fort diamètre, séchés à l'aide de cédules en usage dans l'industrie et rabotés montraient aussi peu que 5 % de rejet. La propriété qui contribuait le plus en termes d'explication de la dégradation était le diamètre. La fibre torse était également importante étant donné l'influence qu'elle peut avoir sur le gauchissement en torsion au séchage. La fibre torse est présente en plus grande quantité dans le bois juvénile, qui constitue une plus grande proportion des grumes de faible diamètre. Les analyses montrent que le diamètre et la fibre torse sont corrélées au gauchissement en torsion. Malheureusement, peu d'informations sont disponibles à propos de la configuration de la fibre torse dans les pins de plantation, et ça n'est que récemment que ce problème s'est attiré toute l'attention qu'il mérite. Les résultats indiquent que le diamètre des grumes de pin radiata est un bon indicateur de la propention au gauchissement en torsion des débits au séchage. Étant donné que cette variable peut être prédite à l'aide de modèles d'aménagement forestier, il est proposé d'étendre le champ d'application de ces modèles pour y inclure la prédiction des rendements en produits finis séchés.

qualité du bois / bois juvénile / défaut de séchage / torsion / modélisation

INTRODUCTION

The economic use of wood for the benefit of mankind depends on an understanding of the anatomical, physical and chemical properties of the raw material. The level of detail required varies with the sophistication of the grower and processor, and the specific end use. In the first instance, broad data (eg, hardwood or softwood) or species information may be adequate for the sale or local use of the lumber, but as the processing industries develop and become more exposed to the pressures of international business, better information on log and lumber properties is needed in relation to specific end uses.

In New Zealand, over 90% of the forest industry is based on only one species (*Pinus radiata*), so quite detailed information is required for internationally competitive industries. Forest management practices have been refined over the past 70 years to allow fast-grown crops of genetically improved trees to be harvested at younger than 30 years of age. Much of the wood quality research has concentrated on describing the attributes of the improved resource in terms of the impact of site factors, silvicultural treatment and rotation age on physical properties such as tracheid length and wood density (Cown, 1992b).

Wood processing industries are now developing international markets based on logs and lumber from young trees with a high proportion of juvenile wood. Therefore, efficient manufacturing necessitates a good knowledge of wood properties and their interaction with product performance. One of the common features of juvenile wood worldwide is its propensity to warp on drying due to the presence of features such as low density, high knot volume, high spiral grain, large microfibril angle, high longitudinal shrinkage and compression wood. This has been reported in several species, including radiata pine (Kloot and Page 1959; du Toit, 1963; Hallock, 1969; Mackay and Rumball, 1971; Balodis, 1972; Gaby, 1972; Kellogg, 1989; Perstorper, 1994).

Studies in New Zealand and elsewhere have demonstrated that drying distortion in pines is an important economic factor in wood processing, particularly in structural lumber. The major problem is twist in excess of grading rules (Haslett and McConchie, 1986). In fact, one of the reasons that high temperature drying of pine framing lumber is gaining popularity is that it is known to reduce the incidence of rejection due to degradation (Weckstein and Rice, 1970; Koch, 1971; Mackay, 1973; Christensen and Gough, 1975; Arganbright et al, 1978; Smith and Siau, 1979; Aleon et al, 1988). Unrestrained drying of radiata pine leads to very high levels of distortion (Mishiro and Booker, 1988).

Practical models have been developed by the Forest Research Institute to link forest management practices to quality characteristics of radiata pine plantation logs. By using regressions based on sawing study results it has been relatively simple to model the yields of undried structural lumber for a limited range of sawing patterns using log variables as inputs–diameter, branch size and wood density and knot size (Program SAWMOD, Whiteside and McGregor, 1987).

The next challenge is to extend the model to simulate the actual recovery of dried marketable lumber, taking into account the considerable drying distortion that can result from the presence of juvenile wood (mainly spiral grain).

The study reported here is an attempt to identify the major log quality and operational factors which can affect drying distortion, based on results from recent sawing and drying studies and to explore the possibility of modeling the effects from log characteristics.

MATERIALS AND METHODS

In recent years a number of sawing and drying studies have been carried out with the objective of quantifying some of the factors known to influence lumber yield and quality. Procedures for sawing studies are standardized to ensure that data are compatible between studies. Individual logs are measured in detail (size, shape, branching, wood density), but unfortunately, due to the time involved, spiral grain measurements are only available for a few of the studies. Research on spiral grain has confirmed that in radiata pine it is a feature largely confined to the inner ten growth rings from the pith (juvenile wood, Cown, 1992a). The extent of juvenile wood is assessed in most sawing studies, as it is felt that the percentage of juvenile wood could be a useful measure in relation to lumber grade recovery and drying distortion.

Log selection and measurement

All the logs in the studies used for analyses were sourced from forests in the central North Island region of New Zealand (table I). Crop ages included in these studies ranged from 21 to 30 years and individual trees were selected in the forest to represent the range of size and branching characteristics present. Average log small end diameter (SED) ranged from 27 to 37 cm. Tree stems were cross-cut to logs, 4.8 m in length, allocated a height class (numbered from the butt) and measured for: large and small end diameters, sweep, average branch diameter, proportion of juvenile wood (ten rings from the pith). In all except the 26-year-old stand, disc samples were removed from each end of the logs and spiral grain assessed by destructive sampling at five-ring intervals from the bark to the pith (Cown et al, 1991) (fig 1).

In these recent studies, all warp values were recorded for each board. In some earlier studies, only the overall percentage rejection rate was recorded (table II); however, these data are still useful for validating the results of model predictions.

Sawing patterns

All logs in the studies were converted to structural lumber using a single or double cant saw pattern, depending on log size. The lumber was measured as 4.8 m lengths, but cross-

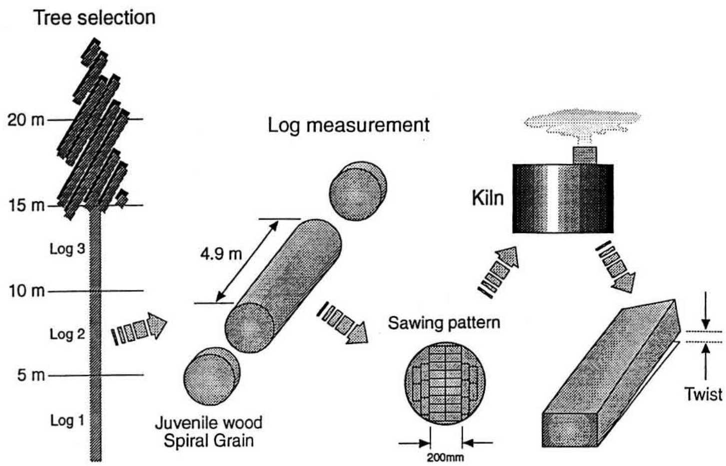

Fig 1. Log and lumber sampling strategy.

sectional dimensions varied between studies so that both domestic sizes (100 x 50 mm) and export sizes (100 x 40 mm) could be assessed (table I). Sizes were not mixed within individual log batches.

Lumber drying

Unrestrained drying of lumber containing juvenile wood leads to very high levels of rejection (Mishiro and Booker, 1988). Increasingly, commercial practice has concentrated on the high temperature drying of structural lumber under weight restraint (up to 1 000 kg/m^2) for both economic reasons and to reduce losses in distortion-prone material (Haslett and McConchie, 1986). Drying methods in the studies reported here included examples of conventional (70 °C) and high temperature drying (120 °C).

Lumber measurement

All lumber was identified by tree and log of origin and graded according to the appropriate domestic or export grading rules. Although grade recovery per se is not discussed in this report, the relationship between grade and distortion was investigated. Drying distortion (twist, crook and bow) was recorded over the full 4.8 m length of the boards and rejection rates determined according to limits in the relevant lumber grading rules. Each piece was also measured for final moisture content.

Model development

The sawing/drying studies reported here have yielded extensive data suitable for developing a preliminary model although not specifically de-

Table I. High temperature drying warp studies.

Stand age (years)	*Lumber size (mm)*	*No of logs*	*No of boards*	*Mean SED (cm)*	*Mean twist (mm)*
21	100 x 40	68	546	27.0	11.3
25	100 x 50	180	1 619	32.0	9.0
26	100 x 40	104	1 415	34.5	8.4
30	100 x 50	49	661	37.1	7.9
30	100 x 40	46	801	37.0	6.4

SED: small end diameter.

signed for the purpose. A pragmatic approach has been to start by analyzing studies which identify the main contributing factors. Data from the trials reported here were used to investigate the influence of resource characteristics such as tree age, log height class, log diameter, branch diameter, spiral grain, lumber grade. In addition, processing factors such as drying method, moisture content, lumber dimensions, lumber machining and grading rule warp allowance were studied.

Previous studies (Haslett et al, 1991) have shown that of the sources of distortion in drying radiata pine juvenile wood, twist is by far the most important factor. On average, in the studies summarized in table I, 99% of the rejected boards had excessive twist. Mean twist was therefore the variable chosen for model prediction, whether assessed in the fresh green or dry condition. In the New Zeland Lumber Grading Rules (SANZ, 1987) maximum allowable twist for 4.8 m structural lumber is 10 mm for 100 x 50 and 15 mm for 100 x 40.

Methods of analysis

The studies summarized in table I were used to identify resource characteristics and processing factors having the greatest influence on twist. Initially, graphical procedures were used, mean twist being plotted against levels of each factor and against pairs of factors. A regression analysis was then performed, and its associated analysis of variance used to test the statistical significance of each variable. The dependent used in this analysis was $\log_e(|\text{twist}|+1)$ which was found to show homogeneous variance and to be normally distributed. Class variables (eg, lumber grade) were fitted using dummy variables.

Having determined the variables most influential in causing twist, a predictive regression model was developed. For this model, twist was analyzed without the log transformation, to ensure that the predictions would be unbiased. Model predictions were validated against the validation data (table II). All analyses were performed using the SAS statistical package.

RESULTS AND DISCUSSION

Conversion from mean twist to % rejection

The variable chosen for analysis from the main data set (table I) was mean twist for each log. For use in the prediction model, and to allow validation of the model against the validation data (table II), it was necessary to derive regression equations relating % rejection to mean twist. Mean twist and % rejection were calculated for each study set after grouping the logs into 10 cm diameter classes. Regression equations were then derived from these data values for each of the two lumber dimensions (fig 2). Means of fewer than 15 boards were excluded from this analysis.

The effect of log characteristics on drying distortion

The log characteristics modeled were: tree age, log height class, diameter, branch size, spiral grain, lumber grade and percentage juvenile wood.

Table II. High temperature drying validation studies.

Stand details	*Lumber size (mm)*	*No of logs*	*No of boards*	*Mean SED (cm)*	*Percentage of boards rejected*
14 years	100 x 50	185	307	25.1	40.0
27–33 years, low density	100 x 40	300	802	36.5	27.5
27–33 years, medium density	100 x 40	300	798	38.7	15.2
27–33 years, high density	100 x 40	300	928	38.6	16.3

SED: small end diameter.

It is well established that younger trees and wood from upper logs are more prone to drying distortion. The study data confirmed good relationships between the degree of twist, crop age and log height class (figure 3). Assuming that logs are converted entirely to structural (as in 'dimension' or 'stud' mills), the best material is clearly from lower logs of older stands. As has been found in practice, the incidence of distortion in lumber from upper logs can be severe. In figure 3 and subsequent graphs, actual mean twist calculated from the data summarized in table I is plotted. Only means derived using more than 15 boards are shown.

In managed plantations of radiata pine there is a correlation between log height class and log SED, as well as with other wood characteristics. It is therefore of interest to investigate the extent to which log diameter by itself can be associated with distortion. Figure 4 shows the study data arranged by crop age and log diameter. In this and subsequent figures, means are shown for SED classified into 10 cm size classes.

The study results strongly indicate that log diameter is the predominant factor affecting drying distortion, and that the 'age effect' already documented is largely incorporated in the effects of changes in log size. Similarly, when the data are examined by log height classes the effect of diameter overpowers that of position in the stem (fig 5).

The percentage of juvenile wood (defined as the inner ten rings) in a board significantly effects its tendency to twist as shown in figure 6. This figure includes the effects of both the age of the log, and the position in the log from which the board was cut. However, when mean twist is obtained for each log, the percentage of juvenile wood in logs of the same SED has a much smaller effect (fig 7). In fact, SED explains much more of the variation in twist than does the percentage juvenile wood in the log. Although there are difficulties in separating the effects of these two variables as they tend to be highly correlated, the analysis suggests that log diameter itself has an impact on lumber warp independent of the effect of juvenile wood.

Spiral grain angle was measured on discs from all logs. Figure 8 shows that logs with greater spiral grain produce lumber with a greater tendency to twist. When compared with figure 7, it appears that spiral grain provides a somewhat better indication of twist than does percentage of juvenile wood.

Logs in New Zealand are often graded according to quality features such as diameter, sweep and branching. It is often assumed that logs with large branches are 'lower quality' due to poorer grade recovery and a greater tendency for drying distortion. The data from the sawing studies confirmed that poorer yields of structural lumber were obtained from large branch (L) logs, but the impact of branch diameter on drying distortion was minimal (fig 9) and related to the small effect of lumber grade (fig 10). There is only marginal reduction in twist as lumber grades improve from X (utility) to 1F (good framing).

The effect of processing variables on drying distortion

While intrinsic log and lumber characteristics are known to be implicated in drying distortion, it is also well known that processing factors play an important part. Information from the sawing studies was used to examine: drying method, moisture content, lumber dimensions, lumber finishing and grading rules.

High temperature drying (> 100 °C) is the preferred method for radiata pine structural lumber because of the demonstrably better economics and the reduced losses due to distortion. (High temperature drying as used in the studies is a commercial operation and includes weighing of the stacks

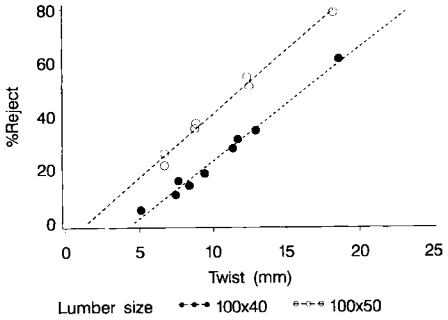

Fig 2. Relationship between % rejection due to twist and mean twist (batch averages). 100 x 40 mm: $y = -19.8 + 4.28x$, $R^2 = 0.99$; 100 x 50 mm: $y = -7.1 + 4.78x$, $R^2 = 0.99$.

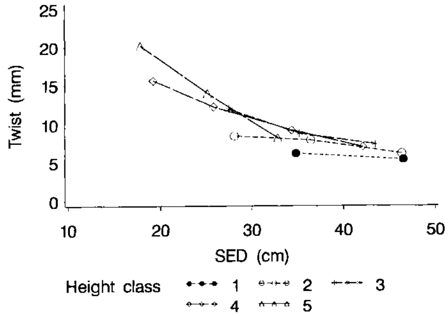

Fig 5. Effect of log diameter and height class on twist.

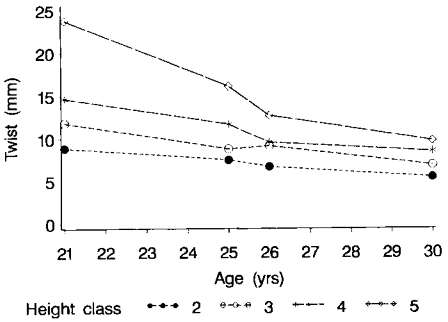

Fig 3. Effect of age and height class on twist.

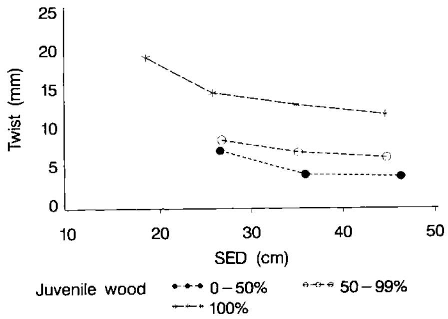

Fig 6. Effect of log diameter and percentage of juvenile wood on twist (individual boards).

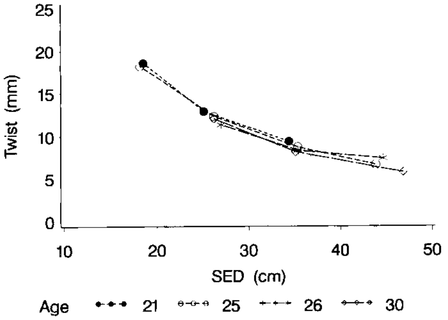

Fig 4. Effect of age and log diameter on twist.

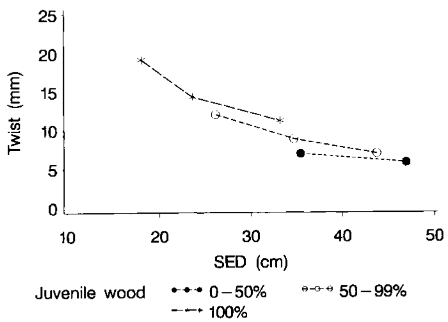

Fig 7. Effect of log diameter and percentage of juvenile wood on twist (log means).

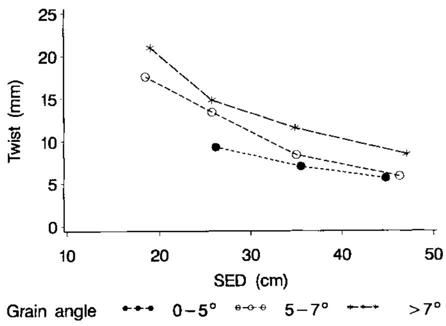

Fig 8. Effect of log diameter and spiral grain angle on twist.

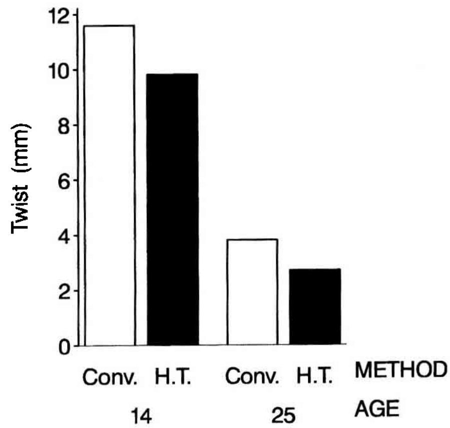

Fig 11. Twist in high temperature (H.T.) versus conventional drying.

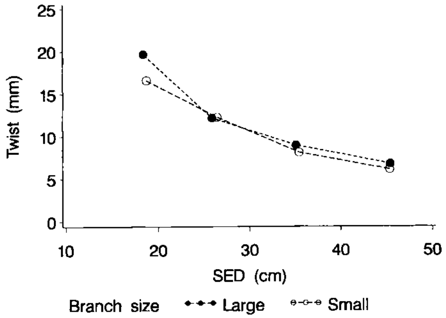

Fig 9. Effect of log diameter and branch size on twist.

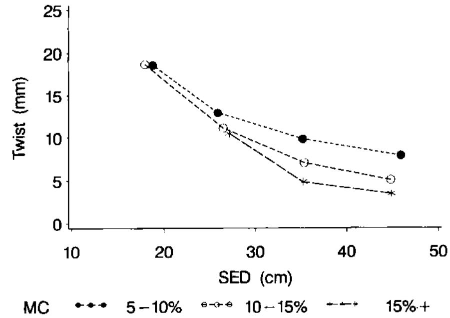

Fig 12. Effect of log diameter and final moisture content (MC) on twist.

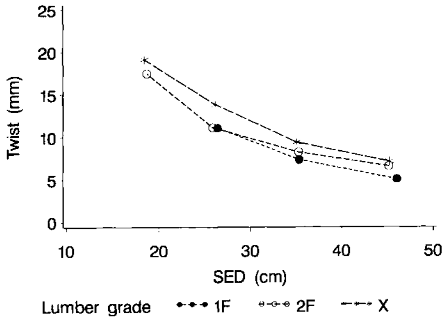

Fig 10. Effect of log diameter and lumber grade on twist.

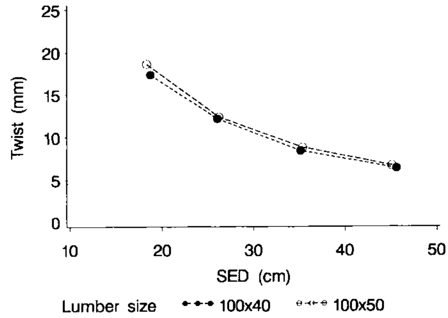

Fig 13. Effect of log diameter and lumber thickness on twist.

and a conditioning period.) Only a limited amount of data are available from research studies on degradation in conventional temperature drying (70 °C). One commercial scale study of 14-year-old 100 x 50 mm boards compared 307 high temperature dried boards with 378 boards dried under a conventional treatment (Haslett and McConchie, 1986). A second study of 25-year-old 100 x 50 mm compared 60 matched boards (ie, each 4.8 m board was cut into two 2.4 m lengths, and divided between the two treatments). These limited data suggest that mean twist using high temperature drying is reduced by about 25% compared to conventional temperature drying (fig 11).

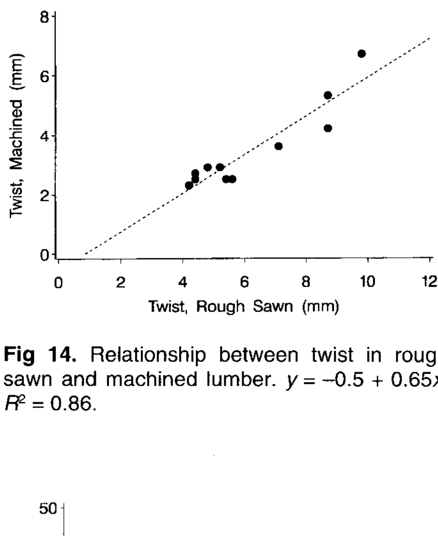

Fig 14. Relationship between twist in rough sawn and machined lumber. $y = -0.5 + 0.65x$, $R^2 = 0.86$.

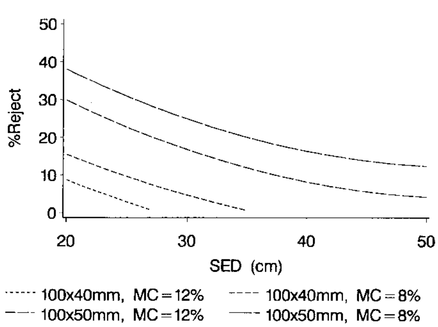

Fig 15. Model predictions of board rejection after machining according to log diameter, lumber dimension and moisture content.

Vitally important is the final moisture content after drying, since shrinkage and distortion increase at lower moisture levels. Hence the tendency to exceed a fixed level specified in grading rules increases as drying progresses towards the required target moisture content, independent of the drying method used. Figure 12 documents the study data according to log diameter and final moisture content. The normal target in New Zealand is 10% for framing lumber. The effect of over-drying is a significant increase in degradation.

The study data gave the opportunity to document the impact of lumber dimension as both 100 x 50 mm and 100 x 40 mm sizes are included in the database. It is sometimes assumed that thinner boards are more easily restrained during drying and conditioning. In fact, the difference due to board thickness is marginal (fig 13).

There is a strong interaction between the amount of wood removed in machining the boards to final dimension and the degree of twist in the product. It is common practice in some sawmills to 'skip dress' to ensure maximum recovery of usable lumber. In other cases, an extra planing allowance may be needed to prevent excessive skip due to distortion (eg, cup in wider boards). In radiata pine the normal planing allowance is 2 mm. In several of the studies, boards rejected due to excessive twist were machined, and the percentage reduction in rejection rate was recorded. A total of 974 boards were machined. Percentage rejection before and after machining were converted into mean twist values using the regressions shown in figure 2. The results (fig 14) show that machining reduced twist by approximately 2 to 4 mm.

Lumber grading rules are formulated by organizations to ensure that standards of quality are consistent. Thus, they are independent of log and lumber characteristics, and subject to periodic review. For instance, the New Zealand rules allow a maximum of 10 mm twist in 100 x 50 mm lumber for domestic use, whereas the Australian rules permit 15 mm in 100 x 40 mm boards.

Analysis of variance of log characteristics and processing factors

The results suggested by the graphs of mean twist versus log characteristics and processing factors were confirmed by an analysis of variance associated with a regression analysis of $\log_e$ (|twist| +1) (table III). The 26-year-old stand was not included in this analysis because it lacked measurements of spiral grain.

The three most important log characteristics were SED, percentage of juvenile wood and spiral grain. These variables are all interrelated as small diameter logs tend to have more juvenile wood which contains greater grain spirality. It was therefore difficult to separate out their individual effects in these studies. However, the factor that explained the greatest variation when fitted initially was SED. Having fitted SED, spiral grain was the next most significant variable. With both SED and spiral grain fitted, percentage of juvenile wood gave only a small though significant improvement in fit. The influence of SED on twist was not due solely to the fact that smaller logs contain a greater proportion of juvenile wood which has higher spiral grain. This was demonstrated by testing SED after first fitting spiral grain to the regression ($F_{1,329}$ = 336.3**). Even with both spiral grain and percentage of juvenile wood in the model, the addition of SED still gave a considerable improvement in fit ($F_{1,329}$ = 96.8**). It was also noted that the log transformation of twist resulted in a linear relation with SED.

After taking account of SED and spiral grain, neither log height class nor branch size were found to have any significant effect. There was also no significant unexplained variation between studies. In other words, factors such as lumber size, stand age and other genetic, environmental or processing effects had no influence on twist which could not be explained by SED, spiral grain and percentage of juvenile wood.

SED, spiral grain angle and height class were measured by log, and were thus tested against the mean square representing the variation between logs (table III). Moisture content and lumber

Table III. Analysis of variance of $\log_e$ (| twist | + 1).

Source of variation	*Degrees of freedom*	*Sum of squares*[a]	F *value*
SED	1	456.3	380.2**
Spiral grain angle	1	155.7	129.7**
% juvenile wood	1	18.6	15.5**
Height class	1	0.20	0.2
Branch size	1	0.32	0.3
Study	3	5.42	1.50
Variation between logs	329	402.1	1.67**
Moisture content	1	164.8	225.9**
Lumber grade	2	14.6	10.0**
Variation between boards	3 259	2 377.6	

[a] Sequential sum of squares - the incremental improvement in error SS as each effect is added to the model; ** statistically significant ($P < 0.01$); SED: small end diameter.

grade were measured by board and were thus tested against the variation between boards. Both were found to have a statistically significant influence on twist in line with figures 10 and 12.

THE MODEL

A regression model to predict losses due to drying distortion, linking log characteristics and processing factors was constructed. This model is currently being incorporated into an existing sawmill processing model.

The model first predicts mean twist for high temperature drying as a function of SED, lumber size (100 x 50 or 100 x 40 mm), lumber grade (1F, 2F or Box) and moisture content after drying, using a multiple regression equation reflecting the relationships described in this paper. The model incorporates quadratic terms for SED and moisture content to take into account the curvilinear nature of the response to these factors. Although spiral grain, and to a lesser extent, percentage of juvenile wood gave statistically significant improvements in fit, they are currently not included in the model. Before they can be incorporated, methods of predicting spiral grain or juvenile wood percentages for individual stands will need to be developed. Neither branch size, stand age nor log height class had a pronounced influence on twist other than that explained by SED, and are therefore not included in the equation. All variables used in the model were highly significant statistically ($P < 0.0001$).

For conventional drying, the predicted mean twist was increased by 25% over high temperature drying (fig 11). The twist reduction for machined lumber was predicted using the regression equation shown in figure 14. The percentage rejection corresponding to predicted mean twist was then calculated using the regression equations shown in figure 2. This figure is slightly increased (by 1%) to include warp other than twist. Example predictions from the model are shown in figure 15.

Validation

The validation data sets (table II) gave the following results. For the 14-year-old stand, actual and predicted percentage rejection was, respectively, 37 and 36% for 1F, 49 and 39% for 2F and 40 and 47% for Box. For the 27- to 33-year-old stands, the actual and predicted percentage rejection was, respectively, 16 and 15% for the high density stands, 15 and 14% for the medium density stands, and 27 and 17% for the low density stands. The predictions are satisfactory except for the low density study. A possible explanation is that these stands had greater grain spirality than the other stands studied.

CONCLUSION

It is important to establish technical and economic relationships between wood properties and final products so that modifications to forest management and wood processing methods result in more efficient and profitable use of plantations.

The expected result of the analyses of sawing studies was that an expression of juvenile wood (eg, percentage of juvenile wood of the log) would be shown to be strongly related to drying distortion. In fact, the data available indicated that log diameter alone is the single most important variable in radiata pine. Spiral grain was the next most important variable. Juvenile wood was closely associated with drying distortion, but only because of its relationship with log diameter and spiral grain. In fact, after these two factors were taken into account, juvenile wood had little additional influence on drying distortion.

Studies designed to link wood and product quality are often carried out in isolation and hence not transportable between researchers. In fact, such studies need to be carefully planned to span the range of conditions used in industry and should have input from commercial operators. The importance of a database cannot be overemphasized. Without the continuity of a sustained research effort and the ability to model and validate results of accumulated studies, little practical progress will be made.

There is still much work for wood scientists to create models to predict effects of wood properties on final products. Interactions at the cellular and ultrastructural level remain to be elucidated. The support for fundamental research is likely to be stronger when empirical models are able to show that the impacts are economically important.

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