METHOD FOR ASSESSING THE EFFECT OF KNOTS IN THE CONVERSION OF LOGS INTO STRUCTURAL LUMBER

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ABSTRACT

A theoretical procedure is described by which the effect of knots in the conversion of logs into structural lumber can be assessed. The procedure features a mathematical algorithm that predicts the outcome of visual stress-grading of lumber carried out in accordance with ASTM D 245. Knots are treated as void areas and logs as perfect cylinders. Log diameter, knot shapes, and the position of sawing planes are used as input parameters.

A numerical example is carried out to quantify the possible improvements in lumber quality from knowledge of the internal knot structure of the log. This example showed significant differences in structural grade yield due to circumferential log orientation.

Keywords: Logs, structural lumber, knots, stress-grading.

INTRODUCTION

In the last several years, the sawmilling industry has made significant improvements in mechanization and automation. A major breakthrough has been the introduction of optical scanners to obtain information about external log characteristics related to shape such as diameter, taper, curvature, and length. This information can be used to select sawing patterns and log orientations that will maximize the volume of lumber sawn from each log. Although several methods (e.g., X-rays, ultrasound) are available to obtain information about internal log characteristics (Han and Birkeland 1992), production-speed internal scanners have not yet been developed. Internal scanning offers potential for increasing the grade yield since major strength-reducing defects could be avoided.

Undoubtedly, knots are the most common internal characteristic that reduces the quality of logs and lumber. A number of studies on structural lumber sawing have indicated that if knot location were considered in the conversion of logs, the grade of lumber sawn from those logs could be increased by the proper orientation of the log on the carriage (Wagner and Taylor 1975; Kato 1976; Kislyi 1983; Shalaev 1983; Nakata 1986). However, the magnitude of variation that exists between grade yields resulting from the best and poorest orientations is not known.

To answer this question, an analytical technique is needed that will: (1) locate the position of each knot in a log, (2) allow several sawing orientations to be tried on this log, and (3) theoretically grade each lumber member obtained from this log. The main sources of variation in the yield, namely knot distribution, log geometry, and log breakdown method, could be examined jointly for their impact upon obtainable grade yield.

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Log breakdown is in essence the fitting of rectangular prisms into approximately cylindrical bodies. This geometrical problem has been actively dealt with in the literature published over the last 30 years. Locating position and recording the size of knots in trees have long been considerations of forestry researchers, although until recently little effort had been devoted to mathematically modelling these parameters. Now, several models are available to describe knots in three-dimensional space (Samson 1993). A review of the current literature suggests that no methodology has been developed to theoretically grade structural lumber members according to knots, rendering the study of the effect of knots on grade yield nearly impossible to carry out.

The objective of the present study was to develop a simulation model for visually stress-grading lumber members according to knots, and to use this model in assessing the effect of knots in the conversion of logs into structural lumber. It was anticipated that relationships between knot distribution, sawing pattern, log orientation, and the structural grade yield could be studied on the basis of computer simulations, thus avoiding laborious physical experiments.

BACKGROUND

Much work has been devoted to developing simulation programs for lumber grading. Programs have been written to grade hardwood (Hallock and Galiger 1971; Klinkhachorn et al. 1988) and softwood (Liljeblad et al. 1988; Leban and Duschanois 1990; Todoroki 1990; Usenius 1990) lumber on the basis of appearance. Since appearance grading is essentially based on the amount of clear wood between defects, these programs cannot be used for structural grading as this depends primarily on knot displacement and eccentricity.

Few researchers have explored the effect of knots on the structural grade yield obtainable from sawlogs. Wagner and Taylor (1975) studied southern pine logs to determine the effect of sawing pattern and circumferential log positioning on the value of lumber theoretically sawn on a chipping headrig. The study logs were cut into disks, and knot location was recorded using a 6-mm grid. A computer program was used to theoretically saw the logs. The computer output listed knot locations only on the two wide faces of the theoretically sawn boards. The authors do not say how the boards were graded, but it is believed that this was done manually. The authors were capable of demonstrating that knotty logs exhibit large variations in yield with changes in circumferential position.

Kislyi (1983) studied the effect of position of the largest knot in cant sawing from a mathematical standpoint. He derived a simple equation relating knot size and board width that served to determine the structural grade of each board. Numerical examples of the effect of knot position on yield were produced using knot data measured on the surface of spruce and pine logs. Unfortunately, Kislyi considered only centerline knots. Almost concurrently, Shalaev (1983) developed statistical prediction on the amount of edge and centerline knots generated in sawing spruce logs. Boards were graded manually with no attempt to use or expand Kislyi's equation. As edge knots are more penalizing than centerline knots, Shalaev suggested orienting the logs during breakdown in such a way that large knots did not occur on the board edges. The effect of log orientation on grade yield was not quantified, suggesting that his conclusions were based on judgement.

MODEL DESCRIPTION

The present model is a mathematical formulation of the ASTM D 245 bending strength ratio concept, which has been adopted by many countries as a basis for establishing grades of visually stress-graded lumber (American Society for Testing and Materials 1988). The ASTM bending strength ratio associated with knots is the ratio of the load-carrying capacity of a member with knots to that of a similar member without knots. This ratio, which ranges from 0 for a completely knotty member to

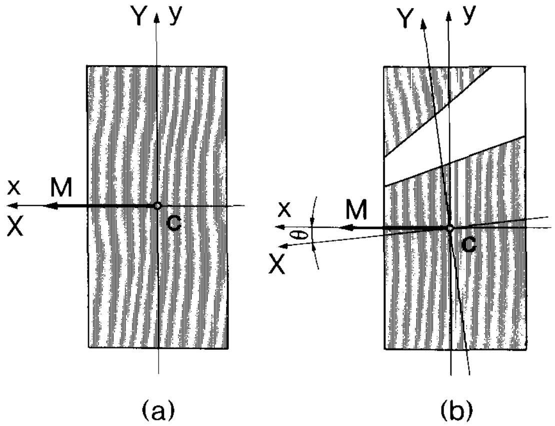

FIG. 1. Schematic representation of a clear (a) and knotty (b) sections showing the couple vector M and the principal centroidal axes cX and cY. The bending plane is inclined by an angle θ with respect to axis cY.

1 for a completely clear straight-grained member, is a convenient quality index in assessing the role of knots in log conversion.

In ASTM, all knots are assumed perpendicular to the surface of the piece and are ideally treated as being either along the edge of the wide face (edge knots), along the centerline of the wide face (centerline knots), or through the narrow face (narrow face knots). Those simplifications, coupled with a complex method of measuring knot size, explain why ASTM gives no general formula for calculating strength ratios.

To facilitate the derivation of a general formula for bending strength ratio (BSR), both a clear rectangle cross section of thickness b and depth d, and a similar section reduced by a knot (treated as a void area) are illustrated in Fig. 1. Coordinate axes cx and cy normal to the wide and narrow faces of the beam locate the centroid c of the section. The bending moment M is assumed to act around the x-axis. It is also assumed that the wood material inside the knot cannot resist any stress and the material outside the knot is homogeneous.

Examination of ASTM D 245 suggests that BSR is the lesser of the following geometric quantities

$$S' = S/S_0 \tag{1}$$

$$A' = A/A_0 \tag{2}$$

where, respectively, A' and S' are the residual area (A) and elastic section modulus (S) of the knotty section expressed as a fraction of the area (A_o) and elastic section modulus (S_o) of the clear section. While A is easily obtained by subtracting the void knot area from A_o = bd, it is not so easy to obtain S because the simple flexure formulas are applicable only when the bending moment acts around one of the principal axes of the section. A section with knots is rarely symmetric and, as shown in Fig. 1, the principal axes xC and cY are usually not parallel to the sides of the cross section. Therefore, the plane of the applied moment will be inclined with respect to the principal axes, resulting in skewed bending. Rotation θ between principal and normal axes can be found from conventional manipulation of moments and products of inertia of the net section calculated with respect to the x, y axes (e.g., Feodosyev 1973). The elastic section modulus can be obtained by expressing the largest stress in the section as a function of the applied moment, and inverting the proportionality term between these two quantities.

For calculating the stress in the knotty section, the applied moment M must be resolved into two components, M cos θ and M sin θ, acting around the X- and Y-axes, respectively. The stress at any point in the section, obtained from superposing stress distributions from each of the moment components, is

$$\sigma(X, Y) = M\left(\frac{X \sin \theta}{I_Y} - \frac{Y \cos \theta}{I_X}\right) \tag{3}$$

where, respectively, I_X and I_Y are the moments of inertia about the X- and Y- axes, and X and Y the coordinates measured in the X-Y plane. From this relation an equation locating the neutral axis can be found by setting $\sigma(X, Y) = 0$. This yields

$$Y = X(I_X/I_Y)\tan \theta \tag{4}$$

The largest stress occurs at the point $P(X_m, Y_m)$ in the net section most distant from the neutral axis. Coordinates X_m and Y_m of this point can be found from the procedures of analytical geometry once the neutral axis has been located. Substituting $X = X_m$, $Y = Y_m$ into Eq. 3, dividing σ by M, and inverting the right-hand side of the resulting equation give the elastic section modulus of the knotty section

$$S = \frac{I_X I_Y}{X_m I_X \sin\theta - Y_m I_Y \cos\theta} \quad (5)$$

Substituting Eq. 5 and $S_0 = bd^2/6$ into Eq. 1 yields the solution sought

$$S' = \frac{6}{bd^2} \cdot \frac{I_X I_Y}{X_m I_X \sin\theta - Y_m I_Y \cos\theta} \quad (6)$$

For a clear section, $\theta = 0$, $I_X = bd^3/12$, $Y_m = \pm d/2$ and S′ reduces to unity.

A computer program was written to calculate A′, S′ and BSR (the lesser of A′ or S′) using as input log diameter, position of the sawing planes, and the parameters necessary to locate a knot in space. Computerized logs are assumed to be perfect cylinders. An example of what can be obtained from the program is given in Fig. 2, which shows three lumber members (A—50 × 180 mm, B—75 × 180 mm, C—50 × 180 mm) theoretically sawn in a 332-mm-diameter log section. The figure shows 4 branches emanating from the pith and the transverse sections of those branches where they intersect the lumber members. For simplicity, all branches are represented as circular cones, normal to log axis, with a 20° vertex angle. Table 1 lists knot characteristics and compares the bending strength ratios for the individual knots obtained from the model to those obtained following ASTM D 245 procedures. ASTM proposes two methods for estimating knot sizes (displacement and surface methods); diameters listed in the table are based on the surface method for knots in joists and planks. Knot type was also determined according to ASTM guidelines. Once knot type and diameter are defined, ASTM BSR is directly obtained from the tables provided in the standard. The close similarity between ASTM and calculated strength ratios suggests that the model can predict reasonably well the outcome of an ASTM-based visual grading process on the basis of single knots.

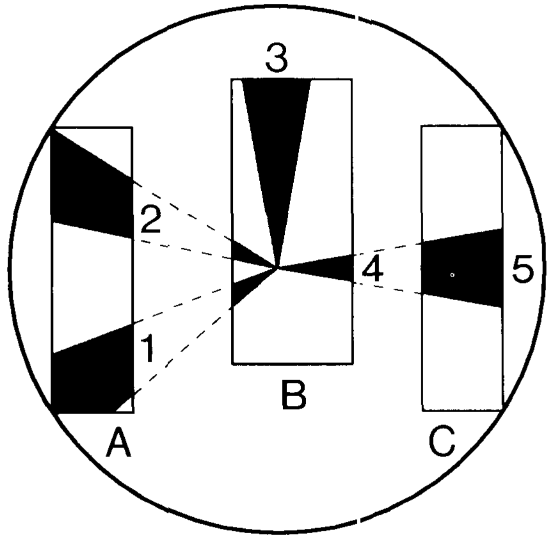

FIG. 2. Intersection of three timber sections (A, B, C) with four branches emanating from the center of a hypothetical section of a log.

As depicted in Fig. 2, it is very likely that in practice more than one knot would appear in a given cross section. ASTM takes multiple knots into account by imposing a limit on the sum of the sizes of all knots in any 150 mm of length of the member. This provision was not incorporated into the present model. Rather, consistent with the approach adopted for single knots, the program calculates A′, S′ and BSR, regardless of the number of knots which might appear in the cross section. According to this procedure, the BSR values for members A and B are 0.25 and 0.57, respectively. For member A, this value is appreciably less than the BSR for the individual knots in the section

TABLE 1. *Comparison of bending strength ratios based on ASTM and calculated with the computer program for the knots shown in Fig. 2.*

Knot number	Knot type	Diameter (mm)	Strength ratios	
			ASTM	Calculated
1	Edge	55	0.52	0.48
2	Corner	35	0.38	0.36
3	Narrow face	42	0.62	0.58
4	Centerline	17	0.92	0.96
5	Centerline	49	0.75	0.78

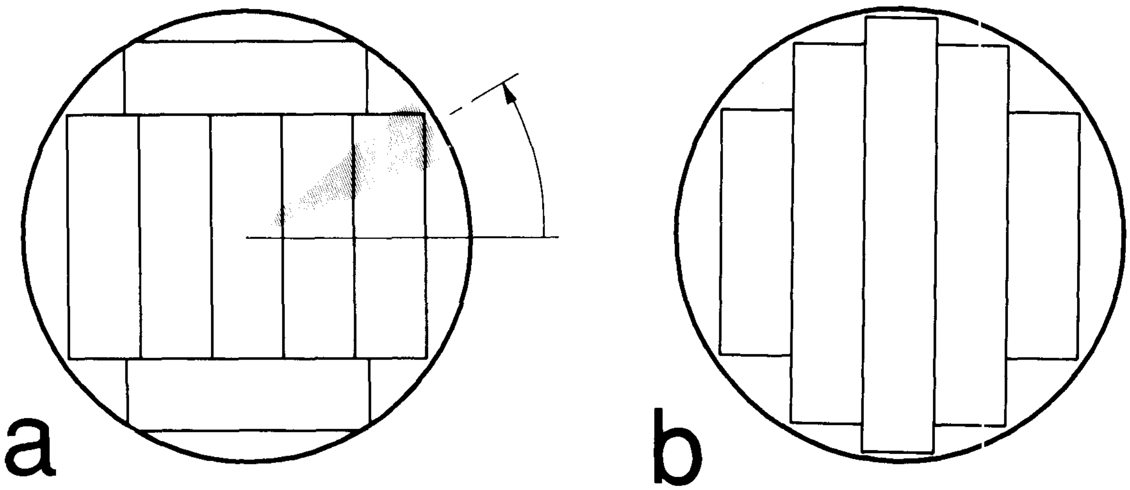

FIG. 3. Log breakdown patterns of the cant (a) and live (b) types used in the numerical example showing the convention adopted for knot rotation.

since both knots have a major influence on strength. On the other hand, the BSR for member B is not materially different from that of the dominant narrow face knot since the small centerline knot has little effect on strength. Both situations conform to expectations based on practical experience.

NUMERICAL EXAMPLE

A numerical example is presented to illustrate a possible application of the model. Calculations are made to study the effect of log rotation on structural grade yield considering various combinations of knottiness and sawing patterns.

Two sawing patterns, illustrated in Fig. 3, representing cant and live processes were retained for the example. Some constraints were applied in selecting the position of the sawing planes to limit the number of variables in the analysis. Logs were assumed to be perfect cylinders, saw kerf was neglected, and no allowance was made for wane. In the solution shown in Fig. 3, all lumber members have a thickness of 0.16 times the log diameter. The slenderness ratio (depth divided by thickness) of the members produced in cant sawing is 3.37, while this ratio for the small, medium, and large sections produced in live sawing is 3.37, 5.25, and 6, respectively. The volume yield expressed as the ratio of the area occupied by the lumber sections to the area of the circle representing the log is nearly the same for the cant (0.77) and live (0.76) sawings. For a log diameter of 250 mm, the actual lumber section sizes in Fig. 3 would be 40 × 135, 40 × 210, and 40 × 240 mm.

Three knot patterns, illustrated in Fig. 4, were considered in the example. Knots have the same characteristics as those studied in the previous section. The patterns differ only by the number of knots in the section and their angular position around the stem (single knot, two opposite knots, and three knots at 120°). Conceptually, these sections would correspond to the only knotty section along the study logs.

Calculations were performed as follows. Starting with the initial position of the knots shown in Fig. 4, the knots were rotated with respect to the sawing planes in 5° increments. This operation, simulating log rotation on a carriage, is illustrated in Fig. 3a for the first knot pattern. After each incremental rotation, the BSR of each individual lumber member was calculated. To account for volume, this BSR value was multiplied by the ratio of the cross-sectional area of the member to the total cross-sectional area of all members sawn in the log. Then the volume-weighted BSR values

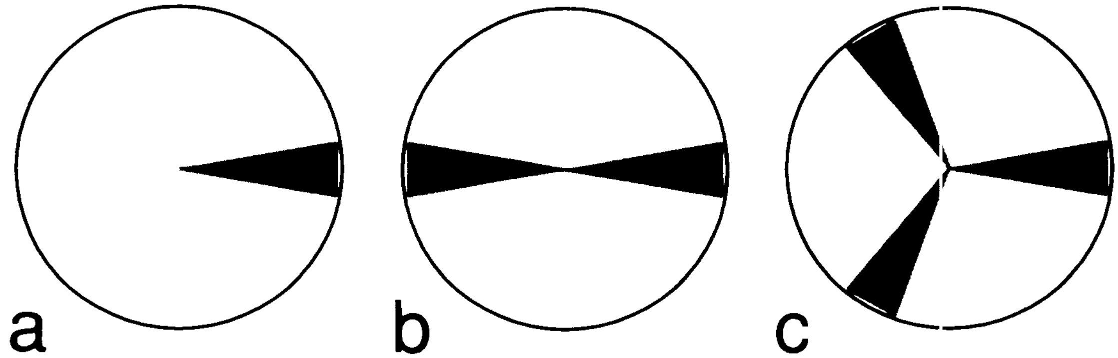

FIG. 4. Knot patterns considered in the numerical example. (a) single knot, (b) two opposite knots, and (c) three knots at 120° angular spacing.

for all members were added to obtain a grade yield expressed as a ratio ranging from 0 (all knotty members) to 1 (all clear members). In comparing cant and live sawing, this grade yield is equivalent to a relative value yield since the volume yields for both sawing methods are practically equal.

The relationships between relative value yield and log rotation within each knot pattern are illustrated in Figs. 5 and 6, for the cant and live patterns, respectively. Owing to symmetry, these functions have a period of 180° when 1 or 2 knots are present, and 60° for the 3-knot situation. Only rotations between 0 and 90° need to be considered since the maximum and minimum yield values occur within this range. Yield functions for the live sawing situation may be regarded as conservative because value premiums normally paid for deeper sections were not considered.

Trends in the yield curves can be verified by laying knot patterns over sawing patterns and identifying the amount of edge and centerline knots created. Comparing curves in Figs. 5 and 6 reveals that, given a knot pattern, the average yield calculated over one period is approximately the same for the cant and live sawings. However, fluctuations about the mean differ greatly from one case to another. Differences in yields between the best and poorest orientations range between 6 and 25 percentage points depending on the case considered. These large differences suggest that log positioning can play an important role in optimizing the value yield from sawlogs. This fact has been recognized in the literature, although the extent to which log rotation could affect structural grade yield could not be quantified. The present model offers potential for theoretically predicting this effect.

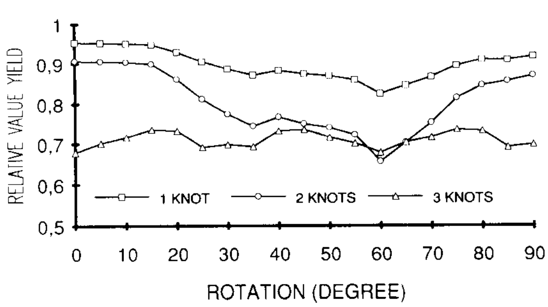

FIG. 5. Relationships between relative value yield and log rotation for the cant sawing situation.

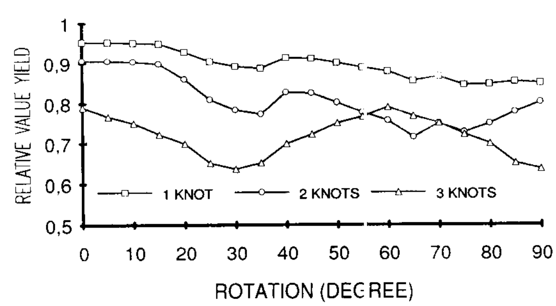

FIG. 6. Relationships between relative value yield and log rotation for the live sawing situation.

CONCLUSIONS

A mathematical formulation based on knot displacement and eccentricity has been developed to estimate the load-carrying capacity of lumber beams in bending, assuming that a knot is a void area and the wood material outside knots is homogeneous. This algorithm approximates bending strength ratio for knots tabulated in ASTM D 245 and can therefore be used to theoretically stress-grade lumber members according to knots.

A simulation model incorporating the stress-grading algorithm was written to assess the influence of knots in the conversion of logs into structural lumber. Using log diameter, knot characteristics, and position of sawing planes as input data, the model can predict grade yield for different circumferential orientations of the log with respect to sawing planes.

A theoretical yield study considering two sawing patterns and three knot configurations in a single knotty section confirmed the effectiveness of sawing logs oriented according to knots. Observation of trends indicates that the model performs as expected. Further studies would be needed to experimentally verify this model. This verification could be accomplished from collecting knot characteristics on dissected logs and conducting statistically sound mill studies.

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