Bending Strength and Modulus of Elasticity of Squares with Wane as Compared with Round Timber of Scots Pine (*Pinus sylvestris*)

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Abstract

A comparison of bending strength and modulus of elasticity (MOE) of squares with wanes to round timber was performed as part of a project on the use of round Scots pine (*Pinus sylvestris* L.) timber in structural frameworks. The study was based on 125 squares and 124 round logs from two sites at high altitudes and two sites at low altitudes in southern Norway. The effects of wanes were estimated by means of reduction in second moment of area and section modulus. Wanes had significant effect on both bending strength and MOE, but in both cases the effects were minor when compared with the effects of material properties. The reduction of bending stiffness due to wanes was almost as much as expected from lack of section, while the reduction of moment capacity was smaller. Squares with ⅓ wane had both lower bending strength and lower MOE than round timber. According to how bending strength and MOE are calculated, differences due to wane were expected. The observed difference in bending strength was larger than expected through the lack of section, indicating that it was affected by material properties as well. The difference in MOE between round timber and squares with ⅓ wane could be explained by the lack of section according to how these values are calculated. Origin had a significant effect on both bending strength and MOE.

This study is part of a project on the use of round Scots pine (*Pinus sylvestris* L.) in structural frameworks, for which the aim is to find new applications for low grades of Scots pine timber. Even if round timber is stronger than sawn timber, many are reluctant to use it because of the round shape and the variations in dimension due to taper. For products such as spars and rafters, and in structural frameworks on which covering materials are going to be mounted, having a constant thickness of the beams is required.

Squares with wanes have been used in agricultural buildings in Norway, and represent one possible alternative. ‘‘Squares’’ is defined in the Nordic rules for visual strength grading (INSTA 142, Standards Norway 1997) as sawn timber with cross section larger than 70 by 70 mm^2, where the largest side is no more than ⅓ wider than the smallest side, and where the pith is located near the center. The requirements for wanes are given as proportions of sawn surface, which refers to the smallest width of sawn surface on each side. According to INSTA 142, ⅔ of any surface shall be machined in grade T1 or higher, while only ½ of any surface is required to be machined in grade T0. European strength classes are defined in EN 338 (European Committee for Standardization [CEN] 2003a), and visually graded timber is assigned to strength classes according to EN 1912 (CEN 2005). Assignment of the Nordic visual grades (INSTA 142) is presented in Table 1, together with those used in the United States.

When calculating bending strength and modulus of elasticity (MOE), it is common practice to ignore wanes and calculate the cross sections as quadratic or rectangular. This has been justified by assuming that increased bending strength and MOE caused by surface continuity of fibers compensate for the loss of cross section. Furthermore, since wane is considered a defect in structural grading, the loss of load-bearing capacity is accounted for by assigning beams with large wanes to a lower strength class or even reject. Martitegui et al. (2007) analyzed the effect of wane on the

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Table 1.—Assignment of grades of conifer species and poplar to strength classes.[a]

Strength class[b]	Grading rule publishing country	Grade[c]	Species	Source
C30	Nordic countries[d]	T3	Pine, spruce, fir, larch	NNE Europe[e]
	United States	J&P Select structural	Southern pine	United States
		SLF Select structural	Southern pine	United States
C24	Nordic countries	T2	Pine, spruce, fir, larch, Sitka spruce	NNE Europe
	United States and Canada	J&P Select structural	Douglas fir, larch, hem-fir, S-P-F[f]	United States and Canada
		SLF Select structural	Douglas fir, larch, hem-fir, S-P-F	United States and Canada
C18	Nordic countries	T1	Pine, spruce, fir, larch, Sitka spruce	NNE Europe
	United States	J&P Select structural	Western white woods	United States
		SLF Select structural	Western white woods	United States
		LF Construction	Southern pine	United States
C14	Nordic countries	T0	Pine, spruce, fir, larch, Sitka spruce	NNE Europe
	United States	J&P No. 1	Western white woods	United States
		J&P No. 2	Western white woods	United States
		SLF No. 1	Western white woods	United States
		SLF No. 2	Western white woods	United States
		LF Standard	Southern pine	United States

[a] Data from EN 1912 (CEN 2005), where scientific names are provided.
[b] According to EN 338 (CEN 2003a).
[c] J&P = structural joists and planks; SLF = structural light framing; LF = light framing.
[d] Nordic countries comprise Denmark, Finland, Iceland, Norway, and Sweden.
[e] NNE Europe = Northern and Northeastern Europe.
[f] S-P-F = spruce-pine-fir.

bending strength of old beams, but found no significant difference between beams with wanes and beams without wanes. They developed a wane factor equivalent to the sectional loss of moment capacity and proposed to reduce the bending strength according to this.

Round timber is expected to be stronger and stiffer than sawn timber because of the surface continuity of wood fibers and because of the radial variation in wood properties (Wolfe 2000, Wolfe and Murphy 2005). Both density and fiber length increase with the number of growth rings from pith (Atmer and Thörnqvist 1982). This transition takes place in the first growth ring from the pith forming ‘‘juvenile wood,’’ as opposed to ‘‘mature wood’’ farther from the pith. Mature wood is denser, stiffer, and stronger than juvenile wood. Retaining mature wood without discontinuities around the juvenile-wood core may provide a bending element with greater strength and stiffness (Wolfe and Murphy 2005).

The superior strength of round timber compared with sawn timber has been emphasized by Ranta-Maunus (1999), who found hand-debarked pine to have higher bending strength than square-sawn pine with equal density. Similar results were found for machine-rounded spruce (*Picea abies*) compared with square-sawn spruce with equal density. In comparison with rectangular-sawn timber from Finland, Ranta-Maunus (1999) found round timber to have higher bending strength but similar MOE.

Sawing may also increase the strength variability, which is crucial since the use of structural timber is based on its characteristic value calculated from the lower fifth percentile. A comparison of round timber strength data to dimension sawn timber strength data showed that strength variability for round timber is about ½ to ⅔ of that of sawn timber (Wolfe 2000). Ranta-Maunus (1999) found the lower fifth percentile of bending strength of round spruce timber to be double that of rectangular-sawn spruce timber if the materials had equal density distribution.

Newlin and Trayer (1924) studied the effect of shape of wood on modulus of rupture (MOR). MOR of round beams with a cross section of 2,580.64 mm^2 (4 $in.^2$) was 1.15 times that of beams with a square cross section of 50.8 by 50.8 mm^2 (2 by 2 $in.^2$). Since the section modulus of the square beam is 1.18 times that of the round beam, they concluded that the load capacities of the two beams are equal if the areas of the cross sections are equal.

Wolfe and Murphy (2005) compared the load capacity of tapered round timber with rectangular timber by means of geometrical considerations alone, presupposing equal material properties. They found that the round tapered section of a log has two to four times the bending load design capacity of any standard-sized timber that can be sawn from it.

The previous studies that have compared round timber strength with square or rectangular timber have not taken wane into account. Since squares often have excessive wanes, this effect has to be tested in order to estimate the load-bearing capacity of such beams. The aim of this study was to analyze the effect of wane on bending strength and MOE of square-sawn timber and to compare the bending properties of square-sawn timber with ⅓ wane with those of round timber.

Materials and Methods

The study was based on 125 squares from 36 trees sampled from four sites in Buskerud County in southern Norway. This is an area where Scots pine is grown at a wide range of altitudes and where it constitutes a substantial part of the wood production. The sites were chosen among those used in a more extensive study of round timber (Høibø and Vestøl 2010, Vestøl and Høibø 2010) and included two poor sites at high altitudes close to the timberline and two more fertile sites located at lower altitudes. The site indices, defined as dominant height at age 40 years, ranged from 6 to 14 m (Table 2). Wood density was higher in the low-altitude sample than in the high-altitude sample, and corresponding differences in the mechanical properties were expected.

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Table 2.—Measures of the sites from where the materials were sampled.

Site	Origin	Altitude (m)	Site index H_{40} (m)	Mean tree age (y)
Flesberg	Low altitude	190	F14	90
Modum	Low altitude	200	F14	90
Blefjell	High altitude	400	F8	130
Flå	High altitude	680	F6	130

The distribution of diameter at breast height was recorded at each site, and all trees with breast height diameter larger than 15 cm were assigned into 3-cm-diameter classes. Then three trees were randomly selected from each of three of the diameter classes, 15 to 18 cm, 21 to 24 cm, and 27 to 30 cm. The sampled trees were crosscut into logs with length depending on the small-end diameter. Minimum small-end diameter was 75 mm. The logs were machine debarked before being sawn into squares with dimensions from 75 by 75 mm^2 to 225 by 225 mm^2 depending on the small-end diameter of the logs. Nominal height was equal to nominal width, and this defined the nominal dimension (*D*) of the squares. The aim was to get squares with ⅔ sawn surfaces and ⅓ wane at the midpoint. Because dimensions were restricted to 25-mm steps, and because of oval cross section, sweep, and abnormal taper, this goal was not always reached, leading to variations in wane both between pieces and also between the sides of a piece. The beams were air dried during summer before being conditioned in a laboratory with a temperature of 20°C and 65 percent relative humidity.

Calculation of wane factors

Wanes were quantified by the wane factor developed by Martitegui et al. (2007) when the squares had wanes on all corners, except that when the squares had different wanes on the upper and on the lower side, this was taken into account. The calculation was based on vertical and horizontal dimensions of the square, width of the upper and lower faces, and mean width of the vertical faces at the point with the smallest cross section between the loading points (Figure 1).

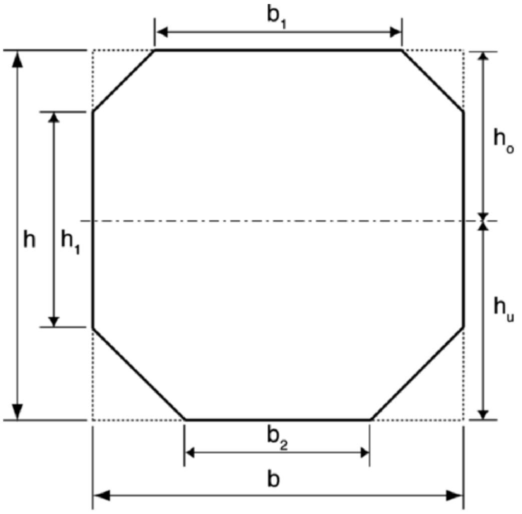

Figure 1.—Measurements of wanes and dimensions.

Wane factor for MOE (ΔI_z) was calculated as the ratio of the second moment of area of the waned cross section (I_{zw}) to the cross section without wanes (I_z). The minimum ΔI_z was 0.600 and maximum was 1.00 (Table 3).

$$\Delta I_z = \frac{I_{zw}}{I_z}$$

Wane factor for bending strength (ΔW_z) was calculated as the ratio of the smallest section modulus of the waned cross section (W_{zw}) to the cross section without wanes (W_z). Since the beams were tested with the side with the most wane facing down, the neutral axis shifted upward in most beams (Figure 1), meaning that the maximum stress in bending was most likely to occur on the lower side. The minimum ΔW_z was 0.567 and maximum was 1.00 (Table 3).

Table 3.—Means, standard deviations, minimum, maximum, and correlations between physical properties of squares of Scots pine timber.[a]

	ΔI_z	ΔW_z	ρ_{12} (kg/m^3)	*D* (mm)	*u* (%)	kd (mm)	kd/*D* (%)	ks (mm)	ks/*D* (%)	ga (%)	arw (mm)
Mean	0.808	0.770	487	129	16.8	28.4	23.8	70.5	59.2	4.1	1.13
SD	0.098	0.113	47	42	1.1	12.3	11.1	33.2	27.2	3.0	0.30
Minimum	0.600	0.567	415	75	15.2	0.0	0.0	0.0	0.0	0.0	0.45
Maximum	1.000	1.000	640	225	20.1	60.0	60.0	178.0	114.0	17.0	2.16
					Correlation coefficients						
ΔI_z	1.000	0.985***	0.211*	-0.061^{NS}	-0.039^{NS}	-0.147^{NS}	-0.144^{NS}	-0.010^{NS}	-0.019^{NS}	-0.011^{NS}	-0.010^{NS}
ΔW_z		1.000	0.233**	0.002^{NS}	-0.007^{NS}	-0.153^{NS}	−0.198*	-0.017^{NS}	-0.068^{NS}	-0.015^{NS}	-0.015^{NS}
ρ_{12}			1.000	-0.074^{NS}	0.103^{NS}	−0.543***	−0.451***	−0.465***	−0.410***	0.003^{NS}	−0.225*
D				1.000	0.683***	0.093^{NS}	−0.526***	0.055^{NS}	−0.529***	-0.054^{NS}	0.208*
u					1.000	-0.079^{NS}	−0.434***	-0.119^{NS}	−0.442***	0.008^{NS}	0.072^{NS}
kd						1.000	0.744***	0.813***	0.619***	0.137^{NS}	0.029^{NS}
kd/*D*							1.000	0.560***	0.837***	0.131^{NS}	-0.061^{NS}
ks								1.000	0.769***	0.005^{NS}	0.148^{NS}
ks/*D*									1.000	0.016^{NS}	0.032^{NS}
ga										1.000	-0.063^{NS}
arw											1.000

[a] *** = $P < 0.001$; ** = $P < 0.01$; * = $P < 0.05$; NS = $P \geq 0.05$.

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$$\Delta W_z = \frac{W_{zw}}{W_z} = \frac{\dfrac{I_{zw}}{\mathrm{Max}(h_u; h_o)}}{\dfrac{I_z}{h/2}}$$

Calculation according to Martitegui et al. (2007) does not take curvature of the log surface into account. This may be justified for squares with small wanes, but not for the squares with excessive wanes that were present in this material. At a certain wane, the calculated cross section will be smaller than it would have been if it had not been sawn at all. In order to find this limit, second moments of area of waned parts of cross sections were compared with calculating these parts as circular sections with radius defined by the width of the beam and the wane on the actual side and the adjacent edges of the vertical sides. The results of these simulations were used as a lower limit for wane factor.

Visual grading

The other physical properties measured on the squares before testing were maximum knot diameter (kd), maximum knot sum (ks), grain angle (ga), and annual ring width (arw). Knot properties and grain angle were measured at the central part of the squares. Maximum knot diameter was measured separately on the tension side and on the compression side of the squares. Because the overall maximum knot diameter gave a better prediction of bending strength, this measure was used in the presented analyses. Annual ring width was measured at the small end of the squares. Means, standard deviations, and correlations between physical properties are presented in Table 3.

Squares were visually graded according to requirements for knots, grain angle, and annual ring width in INSTA 142 (Standards Norway 1997), both with and without taking wane into account (Table 4). Only 31 of 125 squares were accepted for grade T1 or higher, where ⅓ wane is allowed; 76 were accepted for T0 or higher, where ½ wane is allowed; and 49 were rejected (Table 4). Ignoring wane, 122 were accepted for T1 or higher, and all were accepted for T0 or higher (Table 4).

Testing of squares

Bending strength (f_m) and MOE (E_m) of squares were tested in four-point bending according to EN 408 (CEN 2003b). The test was performed with a span equal to 20*D,* the distance between the loading points was 6*D,* and the gauge length for determination of local MOE was 5*D*. The beams were placed with the most wane facing downward toward the side that was subjected to tension stress during bending. Bending strength and MOE were calculated when the cross section was calculated as rectangular based on the vertical and horizontal dimensions measured at midspan between loading points.

Moisture content (u) was measured by the ovendrying method on samples taken close to failure point. Density (ρ_{12}) was measured from the same samples, and following EN 384 (CEN 2004a), it was decreased by 0.5 percent for every percentage point for which the moisture content was above 12 percent. Ranges, means, and standard deviations of moisture content and density are presented in Table 3. MOE and bending strength were increased by 2 percent for each percentage point the moisture content exceeded 12 percent. Squares with a higher moisture content than 18 percent were treated as if the content was 18 percent. In addition, bending strength was adjusted to 150 mm depth by dividing by $k_h = (150/D)^{0.2}$. Nominal dimension was treated as depth in the correction. Since the span in the test arrangement was 20 times depth, bending strength was also adjusted for test length by dividing by $k_l = (l_{es}/l_{et})^{0.2} \approx 0.9919$. Corrections for moisture content on MOE and depth and length on bending strength were performed as described in EN 384 (CEN 2004a), except that corrections were made on individual observations instead of characteristic values. Correction for moisture content on bending strength is not prescribed by EN 384, but it has been shown that such corrections should be performed on round timber (Boren and Barnard 2000). A common correction factor was chosen, since it was assumed that waned squares would perform similarly to round timber in bending.

Table 4.—Results of visual strength grading according to INSTA 142 (Standards Norway 1997).

Grade	EN 338 strength class	Grading result		Grading result ignoring wane	
		No.	%	No.	%
T3	C30	11	8.8	41	32.8
T2	C24	15	12.0	58	46.4
T1	C18	5	4.0	23	18.4
T0	C14	45	36.0	3	2.4
Reject		49	39.2	0	0.0

Round timber

The material of round timber used for comparison consisted of 124 logs from 36 trees sampled from the same sites as those that were tested as squares, following the same sampling methodology. These were part of a larger sample of round timber (Høibø and Vestøl 2010, Vestøl and Høibø 2010). Bending strength and MOE were measured in four-point bending according to Voluntary Product Standard ''Structural round timber—Determination of bending and compression characteristics'' (VPS-SRT-1; Ranta-Maunus 1999), using the same test arrangement as for squares. The testing corresponds to EN 14251 (CEN 2004b), which describes test methods for structural round timber. Bending strength was calculated when the cross section was calculated as elliptic based on vertical and horizontal diameter at the midspan between the loading points. MOE was initially calculated as described in VPS-SRT-1 (Ranta-Maunus 1999), i.e., when the cross section is calculated as elliptic based on vertical and horizontal diameter at the midspan between loading points and then corrected for taper in order to make the results correspond to EN 14251 (Vestøl and Høibø 2010). Values of density and MOE were corrected for moisture content, and values of bending strength were corrected for moisture content, depth, and length using the same correction factors that were used for squares. The range of moisture content in the round timber at the time of testing was from 15.0 to 22.8 percent, with 17.1 percent as a mean.

Statistical analyses

The effect of wanes on bending strength and MOE was analyzed by multiple regression analyses using ΔW_z as an

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Table 5.—Wane factors, density, and mechanical properties of squares with different dimensions.

Dimension (mm^2)	n	Wane factors		Density, ρ_{12} (kg/m^3)[a]	MOE, E_m (N/mm^2)[a]	Bending strength, f_m (N/mm^2)[a]
		ΔI_z	ΔW_z			
75 by 75	19	0.783	0.727	482 (35)	10,193 (3,051)	40.2 (5.7)
100 by 100	35	0.824	0.784	483 (44)	10,732 (2,991)	44.4 (9.8)
125 by 125	26	0.819	0.789	511 (58)	10,964 (3,158)	50.7 (12.6)
150 by 150	16	0.831	0.794	480 (44)	11,319 (3,002)	48.2 (12.0)
175 by 175	15	0.783	0.761	485 (56)	10,435 (3,381)	45.2 (9.6)
200 by 200	8	0.805	0.766	468 (21)	10,649 (1,035)	47.9 (2.5)
225 by 225	6	0.758	0.723	469 (32)	10,453 (1,994)	48.4 (8.1)
All	125	0.808	0.771	487 (47)	10,719 (2,921)	46.1 (10.3)

[a] Values are means (standard deviations).

independent variable for bending strength and ΔI_z as an independent variable for MOE. Since ΔW_z was correlated to ρ_{12} and kd/D (Table 3), these two variables were included as independent variables in the analysis of bending strength in order to correct the effect of wane to equal density and relative knot diameter. Similarly, since ΔI_z was correlated with ρ_{12}, this variable was included as an independent variable in the analysis of MOE in order to correct the effect of wane to equal density. These variables could be included to the models without causing excessive collinearity as long as the correlations were relatively small (O'Brien 2007). Since the main purpose of the models was to estimate the effects of wane, including these variables was necessary in order to avoid confounding between wane factors and correlated wood properties. Collinearities in the models were evaluated by variance inflation factors.

If significant, these models were used to correct bending strength and MOE to squares having ⅓ wane on each side before comparing with round timber. In this case both ΔW_z and ΔI_z were 0.867. Bending strength and MOE of squares with ⅓ wane were compared with round timber by 2-way analysis of variance (ANOVA) using origin as the second variable. The interaction between these two variables was also tested. Hypotheses were rejected if the probability of type I error was smaller than 0.05.

Results

Wane factors, density, bending strength, and MOE for each nominal dimension are presented in Table 5. The values of density and MOE were corrected to 12 percent moisture content, while the values of bending strength were corrected to 12 percent moisture content and 150-mm depth.

The effect of wanes on bending strength is presented in Model 1. R^2 of the model was 0.810, and the root mean square error (RMSE) was 4.53 N/mm^2.

$$f_m = -20.96 + 16.88 \cdot \Delta W_z + 0.128 \cdot \rho_{12} - 0.354 \cdot \mathrm{kd}/D \qquad \text{(Model 1)}$$

The most important factor, by means of the highest F value, was ρ_{12} ($F = 171.0$, $P < 0.0001$), followed by kd/D ($F = 73.8$, $P < 0.0001$). The effect of ΔW_z was smaller but still highly significant ($F = 20.7$, $P < 0.0001$). Removing the effect of ΔW_z, R^2 was reduced to 0.778 and RMSE increased to 4.88 N/mm^2.

Residuals, presented in Figure 2, passed the Shapiro-Wilk W test for normality ($P = 0.5142$). The variance inflation factor was 1.07 for ΔW_z, 1.29 for ρ_{12}, and 1.27 for kd/D, indicating that there is no excessive collinearity in the model (O'Brien 2007). The model is considered to give a valid estimate of the effect of wane within the range of ΔW_z, ρ_{12}, and kd/D, as given in Table 3.

The effect of wanes on MOE is presented in Model 2. R^2 of the model was 0.723, and the RMSE was 1,549 N/mm^2.

$$E_m = -19{,}090 + 10{,}779 \cdot \Delta I_z + 43.32 \cdot \rho_{12} \qquad \text{(Model 2)}$$

The most important factor, by means of the highest F value, was ρ_{12} ($F = 204.7$, $P < 0.0001$). The effect of ΔI_z was smaller but still highly significant ($F = 55.1$, $P < 0.0001$). Removing the effect of ΔI_z, R^2 was reduced to 0.598 and RMSE increased to 1,859 N/mm^2.

Residuals, presented in Figure 3, failed the Shapiro-Wilk W test for normality ($P = 0.0060$), but this was due to one large residual. Since the influence of the observation was small (Cook's distance = 0.05) and since there was no obvious error, the observation was kept in the analysis. The variance inflation factor was 1.05 for both ΔI_z and ρ_{12},

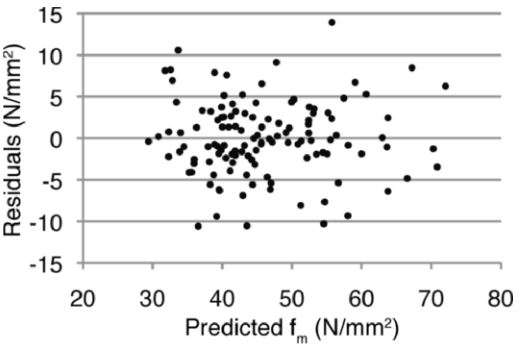

Figure 2.—Residual plot from Model 1.

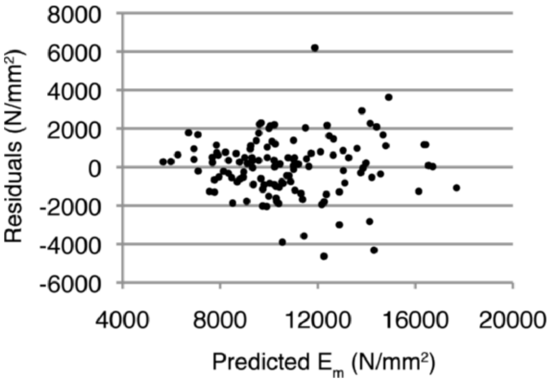

Figure 3.—Residual plot from Model 2.

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Table 6.—Density and mechanical properties of round timber and squares; mechanical properties of squares are corrected to ⅓ wane.[a]

Material	n	Density (kg/m^3)	Bending strength (N/mm^2)	MOE (N/mm^2)
Squares with ⅓ wane	125	487 (47)	47.8 (9.7)	11,394 (2,560)
Round timber	124	487 (47)	62.7 (15.0)	12,872 (3,529)

[a] Values are means (standard deviations).

indicating that there is no excessive collinearity in the model (O'Brien 2007). The model is considered to give a valid estimate of the effect of wane within the range of ΔI_z and ρ_{12}, as given in Table 3.

Means and standard deviations of density, bending strength, and MOE of round timber and squares corrected to ⅓ wane are presented in Table 6. The values of bending strength are corrected according to the effect of ΔW_z in Model 1, and the values of MOE are corrected according to the effect of ΔI_z in Model 2.

ANOVA of bending strength showed a significant difference between round timber and squares with ⅓ wane ($F = 103.8$, $P < 0.0001$), a significant effect of origin ($F = 72.3$, $P < 0.0001$), and a significant effect of interaction between these ($F = 11.7$, $P = 0.0005$). Least square means are presented in Table 7. The interaction effect showed that the difference between round timber and squares was larger for wood from lower altitudes than for wood from higher altitudes.

ANOVA of MOE showed a significant difference between round timber and squares with ⅓ wane ($F = 17.8$, $P < 0.0001$), a significant effect of origin ($F = 91.2$, $P < 0.0001$), and a significant effect of interaction between these ($F = 4.7$, $P = 0.0305$). Least square means are presented in Table 7. The interaction effect showed that the difference between round timber and squares was somewhat larger for wood from lower altitudes than for wood from higher altitudes.

Discussion

Effect of wane on bending strength

Model 1 shows that even if the effect of wane on bending strength is significant, it is of minor importance when compared with the effects of density and relative knot diameter. Significant effect of wane on bending strength was not found by Martitegui et al. (2007). Their study was based on a material with a more limited range of wane, and they did not correct for density or any other wood properties. The group with the most wane in their sample also had the highest density, and this may have influenced the comparison, since our results show that the effect of wane is minor compared with the effect of density.

The reduction of moment capacity ($f_m \times W_z$) described by Model 1 is illustrated in Figure 4 by assuming $\rho_{12} = 487$ kg/m^3 and kd/$D = 23.8$ percent. The second curve illustrates the loss of moment capacity if it is calculated from the loss of section ($f_m \times W_{zw}$) when f_m is estimated from a cross section without wane and the assumptions of ρ_{12} and kd/D are kept equal to the first curve. The loss of moment capacity is only 33.9 percent of what one would expect from the loss of section. One reason for this discrepancy may be that the fracture does not always occur at the smallest cross section. Fracture is often initiated near knots, where the wanes may be smaller due to larger log diameter close to the whorls. Another reason is that the continuous fibers in the log surface that are unbroken in the wanes increase the strength of the beam. This has been used as an explanation for why round timber is stronger than sawn timber (Wolfe 2000), and it may be expected that squares perform more like round timber as the wanes increase. A third reason is that the proportion of juvenile wood decreases with increasing wanes. Since mature wood is denser, stronger, and stiffer than juvenile wood, loss of mature wood in the surface may reduce the bending strength. This effect may be expected to be stronger in logs with few annual rings, where the proportion of juvenile wood is high and may be exposed in the surface of the beams. However, since the material in this study was from old trees, this effect is probably not important for our results.

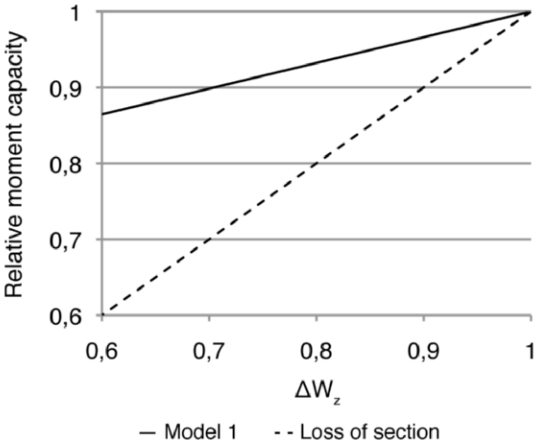

Figure 4.—Effect of wane on relative moment capacity as calculated by Model 1 compared with what one should expect from the loss of section.

Effect of wane on MOE

The effect of wane on MOE described by Model 2 is stronger than the effect on bending strength described by Model 1. Still, the effect is of minor importance compared with density, which explained most of the variation. The reduction of bending stiffness ($E_m \times I_z$) described by Model 2 is illustrated in Figure 5 by assuming $\rho_{12} = 487$ kg/m^3.

Table 7.—Least square means of density and mechanical properties of round timber and squares from different origins; mechanical properties of squares are corrected to ⅓ wane.

Origin	n		Density (kg/m^3)		Bending strength (N/mm^2)		MOE (N/mm^2)	
	Round	Square	Round	Square	Round	Square	Round	Square
High altitude	52	49	462	465	53.0	43.4	10,568	9,877
Low altitude	72	76	505	501	69.8	50.6	14,537	12,373

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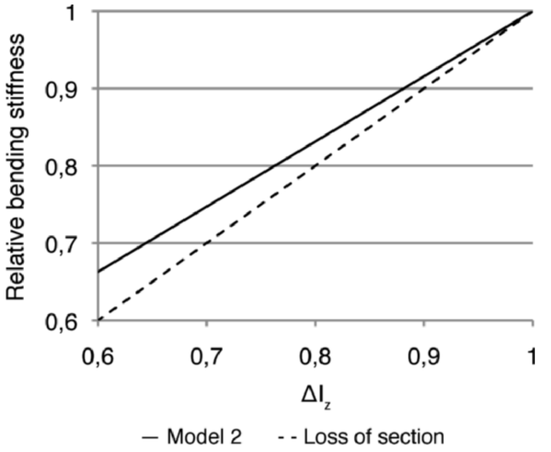

Figure 5.—Effect of wane on relative bending stiffness as calculated by Model 2 compared with what one should expect from the loss of section.

The second curve illustrates the loss of stiffness if it is calculated from the loss of section ($E_m \times I_{zw}$) when E_m is estimated from a cross section without wane and the assumption of ρ_{12} is kept equal to the first curve.

The interpretation of the effect of wane on bending stiffness is not as straightforward as it is for bending strength, since it is not only dependent on the smallest cross section but on all cross sections in the area where the deformation was measured. Only the smallest cross section was measured on this material. Presupposing that wane is constant and equal to the smallest cross section, the loss of bending stiffness is 84.3 percent of what one would expect from the loss of section (Figure 5). Since the loss of cross section is expected to be smaller in other parts of the beam, the estimated loss of bending stiffness ($E_m \times I_{zw}$) is too large. Depending on the taper of the logs from which the squares were sawn, this means that the loss of bending stiffness is at least 84.3 percent of what one should expect from the loss of section.

The effect of continuous fibers in the log surface is probably less important for MOE than it is for bending strength. According to Wolfe (2000), the surface continuity of fibers in round timber prevents the fracture initiation that occurs in sawn timber where fibers around knots are cut and discontinuous. Since this is an effect of fracture mechanics it can be expected to have less influence on MOE. This is observed when comparing round timber and sawn timber where the bending strength deviates more than does MOE (Ranta-Maunus 1999). The effect of removing mature wood and increasing the proportion of juvenile wood is probably small, since the probability of exposing juvenile wood in the surface is low due to the high age of the trees.

Differences between squares and round timber

Mean bending strength of squares with ⅓ wane was 76.2 percent of that of round timber (Table 6). Some of this difference can be explained by the lack of section due to wanes, since squares were calculated based on rectangular section. Not all the difference can be explained this way, however, since round timber has a lack of section due to taper as well. The highest stress in round timber is expected to occur at the loading point closest to the small end, while the bending strength according to EN 14251 (CEN 2004b) is calculated from the cross section at the midspan between loading points. The expected difference between round timber and squares therefore depends on the taper of the round timber. Owing to section, one would expect bending strength of squares with ⅓ wane to be 86.7 percent that of round timber without tapering, and larger if the round timber is tapered. Since the difference is larger, it cannot be explained only by the lack of section but has also to be affected by changes in the material behavior. This corresponds to the result obtained from Finnish spruce and pine, where round timber was found to be stronger than square-sawn timber when density was equal (Ranta-Maunus 1999).

Mean MOE of squares with ⅓ wane was 88.5 percent that of round timber (Table 6). Since tapering was taken into account when calculating MOE of round timber, whereas squares, on the other hand, were calculated based on rectangular section, a difference due to lack of section was expected. MOE of squares was corrected to ⅓ wane, meaning that according to the wane factor (ΔI_z) it is expected to be 86.7 percent of that of a rectangular section without wanes. Since this value is close to the observed difference, the difference in MOE between round timber and squares is mainly explained by loss of section. This corresponds to results obtained on Finnish spruce, where MOE of round timber was similar to that of rectangular-sawn timber, whereas bending strength was higher (Ranta-Maunus 1999).

Effects of origin

Significant effects of origin were expected since the wood from higher altitudes had lower density than that from lower altitudes. During testing it was observed that both round timber and squares from higher altitudes had a higher frequency of brittle fracture compared with materials from lower altitudes, where splintered and ductile fractures were more frequent. While the effect of origin on bending strength was minor compared with the difference between round timber and squares, the results concerning MOE showed that the effect of origin was greater than the difference between squares and round timber. Since the timber from higher altitudes had lower density, this means that MOE is mainly determined by wood properties and does not vary much between round timber and square-sawn timber when the lack of section is taken into account.

The difference in bending strength between round timber and squares was larger on materials from low altitudes than on materials from high altitudes. While mean bending strength of squares from low altitudes was 72.5 percent of that of round timber, the corresponding value for high altitudes was 81.9 percent (Table 7). The effect of fiber continuity on bending strength in round timber may be expected to be smaller in low-density wood where brittle cross-fracture is more likely. Splintering fracture is more likely to occur in wood with higher density, and in this case fiber continuity may be expected to be more important. The lower density of wood from higher altitudes may explain why the difference in bending strength between round timber and squares was smaller than in materials from lower altitudes. There was a similar effect on MOE, but this effect was scarcely significant.

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The coefficient of variation of bending strength was 20.3 percent for squares with ⅓ wane, compared with 23.9 percent for round timber. This result deviates from previous comparisons, which have shown that sawing increases the variability of bending strength (Wolfe 2000). It can be explained by the interaction with origin, since the difference in bending strength between round timber and squares was larger for wood from low altitudes than for wood from high altitudes, and since round timber from low altitudes had the highest bending strength. There was a similar effect on MOE. The coefficient of variation of MOE of squares with ⅓ wane was 22.5 percent compared with 27.4 percent for round timber.

Conclusions and Future Studies

Wanes reduce the moment capacity of squares in bending, but the effect is smaller than one should expect from the loss of section, and it is of minor importance compared with the effects of density and relative knot diameter. Fiber continuity in the wanes is expected to compensate for the loss of section. Since the difference in bending strength between squares with ⅓ wane and round timber is too large to be explained by lack of section alone, it has to be affected by differences in material properties as well. The results indicate that the loss of bending stiffness is close to what one should expect from lack of section, implying that fiber continuity is less important for MOE than it is for bending strength. The difference in MOE between round timber and squares with ⅓ wane can be explained by the lack of section according to how these values are calculated.

The models presented in this study are primarily developed for correcting the mechanical properties of the squares to equal wane in order to enable comparison with round timber. Since the study was based on materials from a limited area and since there are significant interaction effects of origin, the results cannot be generalized without further studies. Such studies should include more detailed descriptions of the geometrical shape of the squares in order to enable a more accurate analysis of bending stiffness. Furthermore, the fracture mechanics of both round timber and squares from different wood qualities need to be investigated.

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