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ORIGINALARBEITEN · ORIGINALS

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Modulus of elasticity of Norway spruce saw logs vs. structural lumber grade

Abstract Structural lumber needs to be stiff, straight, and distortion free to comply with existing international standards. In Sweden there are set standards/certificates (Anon 1995, Anon 2000) that are used to grade structural lumber. As pricing of structural lumber follows the structural lumber grade, there should be large economic benefits from using only saw logs that yield lumber with an acceptable structural grade. In recent years, acoustic technology has been considered as a potential technology for sorting saw logs into classes of modulus of elasticity. The current study, undertaken at a sawmill in central Sweden, explored the agreement between the dynamic modulus of elasticity of 828 Norway spruce (Picea abies) saw logs and structural lumber grade for ca. 2800 pieces of lumber sawn from these logs. The study showed a large span in modulus of elasticity (ca. 9–24 GPa) of logs. A fair agreement was observed between the modulus of elasticity of saw logs (representing two common diameter classes/sawing patterns) and the structural grade of the sawn lumber (according to Anon (1995), Anon (2000)). Thus, by excluding logs with low modulus of elasticity, sawmills could avoid production of low quality/low value structural lumber.

Zusammenhang zwischen dem E-Modul von Fichtenrundholz und den Sortierklassen von daraus hergestelltem Bauschnittholz

Zusammenfassung Nach internationalen Normen muss Bauschnittholz eine gewisse Steifigkeit aufweisen und gerade sowie verformungsfrei sein. In Schweden werden Normen/Zertifikate (Anon 1995, Anon 2000) zur Sortierung von Bauschnittholz verwendet. Da die Sortierklasse des Schnittholzes den Preis beeinflusst, ist zu erwarten, dass sich durch die ausschließliche Verwendung von Stammabschnitten, die Schnittholz akzeptabler Güteklassen liefern, erhebliche wirtschaftliche Nutzen erzielen lassen. In den letzten Jahren wurden akustische Verfahren als mögliche Technologie zur Einteilung von Sägerundholz in E-Modul-Klassen erachtet. Die vorliegende Studie wurde in einem Sägewerk in Zentralschweden durchgeführt. Untersucht wurde die Übereinstimmung zwischen dem dynamischen E-Modul von 828 Fichtenholzabschnitten (Picea abies) und 2800 daraus eingeschnittenen Schnitthölzern. Dabei wies der E-Modul der Stammabschnitte eine große Streuweite auf (ca. 9–24 GPa). Der E-Modul von Sägerundholz (zwei herkömmliche Durchmesserklassen/Schnittbilder) stimmte mit den Sortierklassen des Schnittholzes (sortiert nach Anon (1995), Anon (2000)) ziemlich gut überein. Dementsprechend könnten Sägewerke eine Produktion von minderwertigem Schnittholz geringer Qualität vermeiden, wenn Stammabschnitte mit geringem E-Modul ausgeschlossen werden.

1 Introduction

A progressive shift towards more intensive forest management would mean that trees in the future grow faster and therefore, reach commercial timber size at a relatively young age. This may have severe consequences for primary wood processing industries as a more fast-grown resource, with its larger proportion of juvenile wood, knots, and compression wood, and general wood variation could lead to increased production costs combined with lower prices of solid wood products (Kennedy 1995). In fact, the overall variability in the quality of logs currently arriving at sawmills already implies several advantages of grading and sorting logs before they are processed e.g.:

a) *Avoid logs that yield non-structural lumber.* There would be substantial economic benefits if sawmills could avoid to buy inferior saw logs at full price, process them at high costs and only receive a product with low performance and value. One possibility would be to reject timber that does not meet pre-set structural criteria. Moreover, by replacing poor quality logs with higher-

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grade logs would mean that sawmills increase the production of structural lumber at no additional production cost.

b) *Use best logs for superior products.* The best structural saw logs could be pre-sorted into diameter-, length-, and structural grade which would simplify batch sawing of high-end niche products.

c) *Establish a log pricing system that reflects demand for varying lumber grades.* Provided that mobile log grading systems were developed, log grading and log pricing could be undertaken at time of tree felling. Then systems could be developed that optimised the cross-cutting of trees into saw logs suitable for a pre-defined range of sawn products. In longer term, an improved log pricing system could guide forest owners when contemplating alternative forest management strategies.

In latter years, there have been several research initiatives that aimed to find suitable methods to grade and sort saw logs (Jäppinen 2000, Albert et al. 2002, Beall 2002, Oja et al. 2004). These attempts mirror the need for fast, accurate and non-destructive grading to pre-sort saw logs into objective structural quality classes before processing. (Tsehaye et al. 2000a, Tsehaye et al. 2000b, Roos et al. 2001).

Modulus of elasticity (MOE) is one selection criteria that can be used for log sorting, because MOE has a strong correlation with the use and value of structural lumber as a building material (Kyrkjeedie et al. 1994, Perstorper 1994, Larsson et al. 1998, Tsehaye et al. 2000b, Oja et al. 2001). Moreover, acoustic technology has a potential for measuring MOE of logs quickly and accurately. Currently, acoustic technologies are used in the USA, New Zealand and Australia to segregate trees and timber into discrete quality classes on the basis of MOE (Huang et al. 2003). The study herein investigated the possibilities for acoustic sorting of Norway spruce saw logs (Picea abies) that are mainly used for the production of construction lumber.

2 Objectives

A number of studies, using fast-grown tree species, have shown the possibilities of sorting saw logs into classes of MOE using acoustics for better wood utilisation and product quality (Tsehaye et al. 2000a, Huang et al. 2003, Kliger et al. 2003, Xu and Walker 2004). The current study explored:

1. the approximate variation in MOE in Picea abies saw logs at a sawmill located in central Sweden,
2. the agreement between the dynamic MOE of saw logs vs. structural grade (Reject-C18, C24, C30) of lumber sawn from the same logs,
3. the agreement between dynamic MOE of saw logs vs. the visual grade (Anon 1999) of these logs.

3 Material and methods

3.1 Material

The study was undertaken at Karbenning's sawmill, AB Karl Hedin in central Sweden, with logs delivered from numerous suppliers within the catchment area of the sawmill, which covered a radius of about 100 km north, west and east and 50 km south of the sawmill (equivalent to the area covered by the dotted ellipse in Fig. 1). Logs from Norway spruce (Picea Abies [L.] Karst) ($n = 828$) were sampled from two top-end diameter-classes: 196 (196–206) mm ($n = 387$ logs) and 236 (236–246) mm ($n = 441$ logs). The logs were cut in September 2003 approximately three to six weeks before the measurements were made.

The logs used in this study may have had a larger than normal proportion of logs graded as quality 4, which is a relative poor quality (Table 1).

3.2 Visual grading of logs

All logs were numbered and a grading inspector from the regional timber measurement association (VMF Qbera) classified the logs according to rules and methods that are defined by the Swedish national timber measurement council (Anon 1987, Anon 1999). The following variables were recorded:

Visual log grade (1–4, cull) Logs were visually graded into five classes of potential industrial value.
Log type (1–2) Logs were visually graded as butt- or other logs.
Ring width (1–3) Number (x) of growth rings 2–8 cm from pith were graded into three intervals: $20 \le x$; $12 \le x < 20$; and $x < 12$.
Bow height (1–2) The bow height (b) was measured and the logs were classified into two classes: $b < 1.0\%$ or $1.0\% \le b$.
Compression wood content (1–3) The presence of compression wood in each log was evaluated by visual inspection of the log end surface and the logs were then classified into three classes: no visible compression wood, less than 20%, and 20%–50%.

3.3 Dynamic measurements of log MOE

After visual grading, the logs were measured for resonance frequency with a Rion SA-77 signal analyser connected to an accelerometer. A hammer tap on the log end surface launched a sound wave that caused longitudinal resonance in the log. The logs were lying side by side on two perpendicular logs, either free or in contact with the logs on either side.

Fig. 1 Geographical catchment area of the sawmill
Abb. 1 Einzugsgebiet des Sägewerks

Table 1 Anova tests of Log MOE vs. log variables
Tabelle 1 ANOVA-Tests. Zusammenhang zwischen E-Modul und verschiedenen Eigenschaften der Stammabschnitte

Variable	Class	N	Log MOE (GPa) Mean	Min	Max	Std. dev.	Tukey grouping $\alpha = 0.05$	
Log diameter	196	387	15.7	8.8	23.9	2.4	A	
	236	441	16	9.6	23.2	2.2	A	
Ring width	$20 \leq x$	524	16.4	9.8	18.8	2.2	A	
	$12 \leq x < 20$	268	15.1	9.6	23.3	2.1		B
	$x < 12$	17	14.1	8.8	23.9	2.6		B
Visual grade	1	9	17.9	15.7	19.2	1.3	A	
	2	95	16	8.8	23.9	2.6		B
	3	460	16.2	9.6	23.2	2.2	A	B
	4	234	15.2	9.2	22	2.2		B
	Cull	11	14.7	9.8	17.9	2.4		B
Compression wood content	no visible	444	16.1	9.8	23.9	2.3	A	
	< 20%	257	15.7	8.8	23.2	2.2	A	
	20%–50%.	127	15.1	9.2	19.4	2.1		B
Bow height	< 1%	777	15.9	8.8	23.9	2.3	A	
	> 1%	32	14.7	9.2	18.9	2.2		B
Log type	Butt log	509	15.8	9.2	21.9	2.2	A	
	Other log	300	16.1	8.8	23.9	2.5		B

The sound wave velocity was measured using the following equation:

$$V = 2lf \tag{1}$$

where: l is equal to the length of the log and f is equal to the fundamental resonance frequency given by the graphical display on the signal analyser. The l was measured to the nearest cm and given as a manual input to Eq. 1. The MOE can then be calculated using Eq. 2:

$$\mathrm{MOE}(Dynamic) = \rho V^2 \tag{2}$$

where the green density of the logs, ρ, was assumed to be 1000 kg/m^3. Some variability may occur due to the green density of Norway spruce logs, ρ, may vary between 700–1050 kg/m^3 dependent on primarily heart wood percentage, storage time, exposure to water, and the time of the year when a tree is felled (Nylinder 1961). It might be reasonable to assume that the green density could be adjusted based on the aforementioned variables, or even directly determined by using scale and volume measurements to allow for a more accurate MOE calculation. However, as the logs were cut in autumn, the green density of the logs was assumed to be 1000 kg/m^3.

Fig. 2 Logs during measurement
Abb. 2 Messung der Stammabschnitte

To simplify, Eq. 2 can be substituted directly into Eq. 1 for transformation to Eq. 3:

$$\mathrm{MOE}(Dynamic) = 4\rho l^2 f^2 \tag{3}$$

where: ρ is set to 1000 kg/m^3, l is equal to the length of the log, and f is equal to the fundamental resonance frequency.

3.4 Sawing pattern and machine stress grading of boards

The 387 logs within the diameter class 196 mm were cut into four centreboards with the dimension 34 mm × 112 mm (Fig. 3a). The logs with dimension 236 mm were cut into three centreboards with the middle centreboard cut to 47 mm × 175 mm and the two outer centreboards cut to 42 mm × 175 mm (Fig. 3b). The dimension 34 mm × 112 mm is a product for the Japanese market used in glulam beams for house production. The dimension 47 mm × 175 mm is a product for the Swedish and European market used for panels and 42 mm × 175 mm is a product for the Japanese market used to manufacture construction and building components.

All boards were placed in conventional stacks and then kiln dried using a conventional drying scheme. The boards with the dimension 34 mm × 112 mm were dried to 13% moisture content (MC). The boards with the dimension 47 mm × 175 mm were dried to 18% MC, and boards with the dimension 42 mm × 175 mm were dried to 18% MC.

After drying, all boards were stress graded with a Cook-Bolinder-machine (Boström 1999). The boards were graded into three structural grades: C30, C24 and C18 according to current

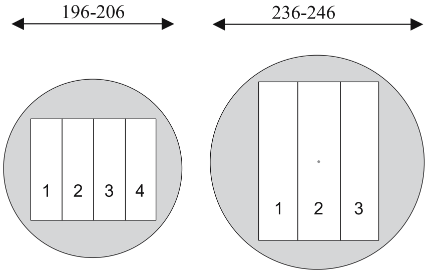

Fig. 3 a (196 mm), **b** (236 mm). Sawing patterns used for each log diameter class
Abb. 3 Schnittbilder der beiden Durchmesserklassen **a** 196 mm; **b** 236 mm

Swedish grading rules for structural lumber i.e. SS-EN 519 and SPCR 078 (Anon 1995, Anon 2000). Following the same guidelines, visual inspection was used to sort boards into a reject class, which was combined with the structural C18 grade. Unfortunately there was no possibility to separate the C18- and reject class in the further analysis.

3.5 Statistical evaluation

All statistical evaluation was done in the statistical software SAS 8.2 (SAS Institute 1999). Generalized linear modelling (GLM) was used to study the relation between: dynamic MOE vs. visual grading and dynamic MOE vs. current Swedish timber grading rules (Anon 1999). To adjust for mass significance the Tukey method was used and the significance level was 5%.

Board strength class and the board's closeness to pith were evaluated with a Chi-square test using SAS Freq procedure for the boards cut from log dimension 236. This method measured the association between the two groups: boards cut close to pith and away from pith. The evaluation compared the frequencies of boards in the three board strength classes, for all boards and for each of three log MOE classes.

4 Results

4.1 Relationship between log MOE vs. structural lumber grade

The distribution of log MOE (bars) of all 828 logs is shown in Fig. 4 together with the outcome of board volume for the three different lumber strength classes (represented as lines). The structural grade distribution of the sawn lumber changed within the log MOE range, for instance, the share of C30 lumber increased from 23% in the lowest log MOE interval (MOE < 10 GPa) to 91% in the highest (MOE > 20 GPa), the most pronounced increase in lumber strength grade C30 was found for the lower log MOE intervals (Fig. 4).

4.2 The relation between log MOE vs. visual log grading variables

Tests were conducted to determine if log MOE means differed, and the means for the following variables were tested: log diameter, ring width, visual grade, compression wood content, bow height, and log type. As the interactions between these latter variables were not relevant, one-way ANOVA was performed between log MOE and the different variables. The Tukey method tested significant difference in means at the 5% level.

The means for log MOE varied significantly for the variables, except for log diameter, as presented in Table 1 where classes with the same letters in the right column had no differences in means.

Though the relationships between visual grade classes and log MOE appeared relatively weak, i.e. individual logs within each separate visual grade had quite differing log MOE. Despite differences between visual grades, the visual grading system and the MOE of logs had low agreement. For instance, individual logs that displayed poor visual grade still had high MOE, meaning that they were likely to produce good construction lumber. Likewise, some logs with high visual grade have low MOE. The visual grades are though constructed to consider not only suitability for construction.

4.3 The influence of log MOE and sawing position on construction lumber grade

During test sawing, large numbers of logs were processed at great speed and there was limited possibility to mark the sawing position of the lumber. However, for the logs representing the top-end diameter class 236 mm sawing pattern (Fig. 3b, Table 2) it was possible to distinguish lumber cut close to pith from lumber cut away from pith.

Table 2 depicts the influence of log MOE and sawing position on construction lumber grade. Various combinations of log

Fig. 4 Structural lumber grade distributions within log MOE intervals
Abb. 4 Ausbeute in den Sortierklassen in Abhängigkeit des E-Moduls der Stammabschnitte

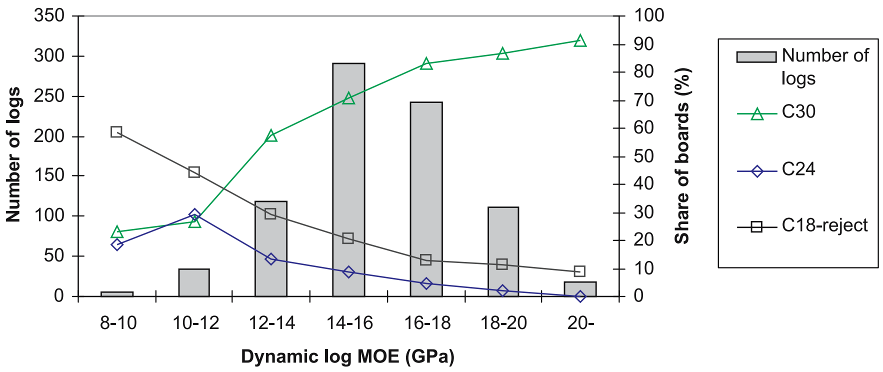

Table 2 The proportion of lumber in stiffness classes from the juvenile and mature part of saw logs arranged by low-, medium-, and high log MOE interval class for logs with top end diameter 236 mm

Tabelle 2 Schnittholzanteil in den Steifigkeitsklassen aus juvenilem und adultem Holz der Stammabschnitte mit einem Zopfdurchmesser von 236 mm (unterteilt in Abschnitte mit geringem, mittlerem und hohem E-Modul)

Boards dimension and sawing position	Board strength class	Log MOE (share of board volume %) < 14 GPa	14–18 GPa	> 18 Gpa
47*175 (cut close to pith)	C30	35.4	71.7	84.0
	C24	18.5	11.6	2.7
	C18-reject	46.2	16.7	13.3
	Total	100	100	100
42*175 (cut away from pith)	C30	49.6	83.2	91.6
	C24	20.9	5.6	1.4
	C18-reject	29.6	11.2	7.0
	Total	100	100	100
Test for equal distribution of board strength classes by sawing position	Chi-square (2 df)	5.74	16.82	3.73
	P	0.057	0.0002	0.154

MOE/sawing position will yield differing proportions of construction lumber grade. For instance, high MOE logs were found with a statistically lower proportion of lumber classified as C18-reject lumber compared with logs with low MOE. There was also a grade difference (Chi-Square $p < 0.0001$) between lumber cut close to pith and lumber cut away from pith (not considering log MOE). When the analysis was repeated using a Chi Square test separately on three intervals of log MOE, the importance of closeness to pith differed (Table 2). In the medium log-quality group (log MOE 14–18) strength properties differed (Chi-square: $p = 0.0002$) between boards cut close to pith and away from pith. In the high log-quality group (log MOE > 18) the difference in construction grade between the two groups was not significant (Chi-square: $p = 0.154$). In the group with low log MOE, the difference was only significant at the 10% level (Chi-square: $p = 0.057$).

5 Discussion

One main result of this study was that saw logs with low MOE yield lumber with low structural grade (Fig. 4, Tables 1, 2). From Fig. 4 it was clear that the structural grade distribution of the sawn lumber correlated with the measured log MOE. The amount of C30 boards increased from 23% for logs with MOE < 10 GPa to 91% for logs with MOE > 20 GPa. In theory, if logs having an MOE of less than 12 GPa were rejected, representing ca. 5% of the total number of logs, it would mean considerable improvement in the volume of approved structural lumber. Moreover, producing lesser quantities of low grade structural lumber would probably mean fewer dissatisfied customers and a higher average product price on construction lumber.

Even after rejection of logs with low MOE, the sawing patterns used in traditional milling mean that much lumber will be cut close to pith from juvenile wood. Lumber cut close to pith has less desirable properties, i.e. considerable drying distortion with low stiffness and strength. This was illustrated by comparing structural grade of lumber cut close to pith vs. away from pith (Table 2). This may also explain why some lumber (ca. 10%) has C18-reject grade even when cut from logs with high MOE. Alternatively, the C18-reject grade proportion might be about constant within each log MOE interval because of various defects in the lumber. Unfortunately, machine stress grading requires the combining of strength grades C18 and rejects, and thus blocks any further analysis.

For logs in the best structural group interval (log MOE > 18 GPa, Table 2), no statistically significant difference in lumber grade was detected for lumber cut close to vs. away from pith ($p = 0.154$). This result differed from what was seen in the other log MOE intervals used in Table 2, where the differences in lumber grade were significant at the 10% level ($p = 0.056$) for the lowest log MOE group and strongly significant ($p = 0.0002$) for the intermediate log MOE group. This implied that sawing patterns could be developed to improve control of the gradients in MOE from pith outwards when using logs of low and intermediate structural grade. Control of the internal structural grade variation of logs might be achieved by more sophisticated sawing patterns giving rise to lumber with more consistent structural grade. To some extent, this principle is already used commercially at many sawmills, e.g. the sawing pattern for the logs with dimension 236 are cut using a wider lumber dimension for the centre of the log to cover the pith and to concentrate the juvenile into one lumber piece. This produces a lower average structural grade for lumber cut close to pith, at the same time leaving two pieces of lumber that theoretically will be cut from more mature wood. Whether there is potential of further development is an open question. For instance, it may be that logs that have been pre-sorted into discrete log MOE classes could be assigned specially designed sawing patterns. Used in batch sawing this would allow production of lumber that satisfies customers requiring specific structural lumber properties for use in e.g. glulam beams.

Based on the data from this study it appears that the main acoustic sorting possibilities require a threshold value taken as an offset value to avoid logs having low MOE (Fig. 4, Table 1). Moreover, the results indicated the possibilities of grading logs into MOE intervals that are linked with the structural grade of the sawn lumber. This opens the possibility of selecting logs to match a given customer order with current wood resource in the log yard and the physical production limitations of the individual sawmills. From the results of this study and based on the knowledge of log MOE, there appears to be possibilities for empirically establishing sawing patterns that could yield lumber with more homogenised properties. These possibilities could lead to sawmill production being more adapted to customer requirements.

Statistical agreement between log MOE vs. visual log grading variables. There was variation in the means for the classes in the registered variables presented in Table 1, except for log diameter, this may be due to log diameter being a compound variable of growth rate and tree age. This means that a low log diameter may be the result of many and narrow growth rings (old trees) or few and wide growth rings (fast grown younger trees). The logs with compression wood and/or curvature had slightly lower MOE than other logs, a result that confirms the studies by Johansson et al. (1992) where compression wood in Norway spruce was found to be correlated with poor strength. Thus, relatively low MOE seen in logs with large bow height could be a consequence of the correlation between compression wood and bow height (Öhman 1999). Difference in log MOE was significant between visual log grades; this was expected as properties that cause logs to be downgraded are normally correlated with properties that cause low MOE. A small difference in log MOE could be shown between log types where butt logs had a lower MOE than other logs. Xu and Walker (2004) have determined this for Radiata pine. Nevertheless, it is clear from the wide log MOE variation within each visual grade class, that log MOE is not a good predictor of a log's visual grade; likewise, visual grade cannot be used as a good predictor of the MOE of an individual log.

In theory, logs with low MOE have a high degree of juvenile wood with short fibres, large microfibril angle- and spiral grain (Huang et al. 2003), which is typical for trees/logs that combine fast growth with few growth rings. At the same time, there is evidence of genetic MOE differences between trees (Lindström et al. 2002, Lindström et al. 2005). Together with variation in tree age (total number of growth rings in a log), this may explain why MOE varied widely within each of the three ring width classes. Knot volume and the green density of logs were not measured in this study, which also could have explained some of the variation in log MOE. If machine stress grading had been designed to produce a continuous value of lumber stiffness rather than the direct classification of structural lumber grade class (cull, C18, C24, and C30), further analysis would have been possible. For instance, a large share of the lumber was classified as the best structural lumber grade (C30) whereas superior lumber grades (C35, C35+) were not used. Although no machine stress grading data is available to distinguish between C30 and higher structural grades it is likely that even higher structural grades could have been demonstrated. Moreover, the enforced combination of strength classes cull and C18 could possibly have led to the higher log MOE of this class compared to C24. (Anon 1995)

5.1 Future work

Although it appears possible to sort saw logs into MOE classes, there is still a need for further studies on:

1. The influence of green log density/moisture content (fresh – dry) on log MOE
2. The influence of log temperature (unfrozen – frozen) on log MOE.
3. The theoretical possibilities of segregating logs with internal structural gradients with a set of acoustic methodologies (Lindström et al. 2005).

If such studies show that there are small differences in MOE caused by log density and temperature and/or that such differences can be compensated for by empirical functions, it could be possible to develop automated sorting systems based on acoustic technology for commercial log sorting.

6 Conclusions

This study showed that there is agreement between the modulus of elasticity of Norway spruce saw logs and the structural grade of sawn lumber. The study confirms earlier results that acoustic technologies may be useful in grading logs into stiffness/structural grade classes. However, further studies should be undertaken to clarify the effects of green log density, moisture content, and temperature.

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