Holz als Roh- und Werkstoff 56 (1998) 331–338 © Springer-Verlag 1998

Mechanical properties of sawn timber from Norway spruce

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Dynamic and static tests were performed on 523 lumber specimens of Norway spruce (*Picea abies*) of three different cross sectional sizes: 38 × 89 mm², 38 × 140 mm², and 38 × 184 mm². Specific material characteristics for the lumber are presented. The tests also enabled comparison between results from two testing methodologies. The mean value for the modulus of elasticity established from the dynamic tests was found to be approximately 10% higher than the corresponding value established from static tests. The statistical correlation between statically and dynamically established moduli is very strong. The dynamic E modulus was found to be as good a strength predictor as the static E modulus. Cross sectional size and the existence of the pith in the sawn lumber were found to significantly influence the material properties. In general terms, it was found that deeper beams correspond to lower values for the E modulus and for the bending strength. The reason for this tendency is believed to be a combination of a volumetric effect (in the case of strength) and a phenomenon related to the log selection and sawing process in the mills. Lumber that comprises the pith has been found to have generally lower values of the E modulus and bending strength while the shear modulus is higher, compared to lumber without pith sawn further out in the log.

Mechanische Eigenschaften von Fichtenschnittholz

An 525 Schnittholzproben (*Picea abies*) wurden dynamische und statische Prüfungen vorgenommen. Die Proben hatten drei verschiedene Querschnitte: 38 × 89 mm², 38 × 140 mm² und 38 × 184 mm². Anhand der vorgelegten Ergebnisse wurden auch zwei Prüfmethoden verglichen. Die Mittelwerte der dynamischen MOE-Prüfung lagen etwa 10% höher als die statisch ermittelten Werte. Die Korrelation beider MOE-Werte ist sehr streng. Beide Werte können zur Vorhersage der Festigkeit verwendet werden. Der Querschnitt und die Anwesenheit von Markanteilen beeinflussen das Ergebnis wesentlich. Je tiefer die Balken waren d.h. je näher sie der Markröhre lagen, desto geringer waren E-Modul und Biegefestigkeit. Die Gründe dafür werden teils einem Volumeneffekt zugeschrieben (im Falle der Festigkeit), teils auf das Auswahlverfahren der Stämme im Sägebetrieb zurückgeführt. Schnittholz mit Markanteil hatte allgemein. einen geringeren E-Modul und niedrigere Biegefestigkeit als Proben aus äußeren Stammbereichen; die Scherfestigkeit lag dagegen höher.

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The dynamic tests and subsequent evaluation and comparison between dynamic and static test data were made within a project concerning the determination of viscoelastic properties of anisotropic materials by modal testing, which is financially supported by the Swedish Research Council for Engineering Sciences (TFR) in grant No. 261-94-344; this is gratefully acknowledged.

1 Introduction

Several methods for the evaluation of mechanical timber properties exist. A method based on forced vibration testing and subsequent spectral analysis is utilised here together with classic static bending tests. In this paper, the results of dynamic and static tests on 523 samples of Norway spruce (*Picea abies*) are presented.

The number of studies reported in literature that comprises both dynamic and static tests is limited, especially with respect to Scandinavian conifers. Kollmann and Krech (1960) have determined the longitudinal E modulus from dynamic and static tests for small clear specimens (8 × 10 × 200 mm³) of spruce (*Picea excelsa L.*). They showed that the dynamic E modulus was on average 4% higher than the static one. The shear moduli in the longitudinal/tangential and in the longitudinal/radial planes were established by utilising the secondary effects of shear deformation and rotary inertia of the cross sections on the bending modes of vibration of the small clear specimens. Four or five higher order modes were used for the shear moduli determination. Ohlsson and Perstorper (1992) have conducted vibration tests on a relatively clear sample of Norway spruce (*Picea abies*) with the dimensions 62 × 282 × 1800 mm³. They showed that the E modulus determined from bending and longitudinal modes of vibration and the shear modulus established from torsional vibration modes can be used to calculate the resonance frequencies of bending modes with short modal wave lengths for structural timber. Perstorper (1994) have presented results from several non-destructive test methods applied to beam specimens of Norway spruce (*Picea abies*) with cross sections of 70 × 290 mm². The values for the E modulus established from dynamic tests incorporating edgewise bending modes were on average 3% higher than the static ones established from classic four-point edgewise static bending tests. The corresponding figure was equal to 7% for the E modulus evaluated from flatwise bending modes of vibration. It seems clear that, although test procedures may differ among the studies found in the literature, the dynamically evaluated E modulus is generally found to be somewhat higher than the static one.

2
Objective

The main objective of this study was to establish dynamic and static elastic constants and bending strength values for Norway spruce timber of different categories. The influence on these properties from the variation in timber size and the inclusion or exclusion of the pith was also of interest. Comparison between the dynamic and static properties and some physical properties was also included in this study.

3
The material

The material was collected from six Swedish sawmills located in the northern, middle and the southern parts of Sweden. Mean values and standard deviations of the established raw material properties of the timber batch are presented in Table 1.

4
Dynamic tests

4.1
Test procedure

Dynamic tests were performed on each lumber specimen. The tests comprised three types of vibrations: longitudinal, edgewise bending and torsional vibrations. For each type of test, the specimens were arranged so that they could be regarded as having totally *free* boundaries; for detailed test information see Larsson et al. (1997).

The bending vibration tests were performed by using a miniature accelerometer (PCB 302 A02, mass 3 g) and a light hammer instrumented with a force transducer (PCB 208 A04). In order to monitor the three types of vibration, each specimen was tested in three different ways. For the edgewise bending vibration tests, the accelerometer was fastened on the edge side, close to one end of the beam, and oriented so that it could measure vibrations in the beam depth direction. The impact force was applied at the same location and direction. The torsional vibrations were detected likewise, but by measurements on the flat side of the beams and by allowing for an eccentricity, with respect to the centre-line of the beam, for the applied load and response. The longitudinal vibrations were excited by applying an impact force to the beam end and measurement of the response was made at the same location with an accelerometer orientated in the longitudinal direction of the beam. All measurement signals were acquired and digitised by the use of a frontend (Hewlett Packard 35651B) controlled by the CADA-X software from Leuven Measurement Systems. The resonance frequencies were determined in the CADA-X software by picking the maximum peaks in the created frequency response functions. Each peak represents a vibration mode with its corresponding resonance frequency. The accuracy of the values of the determined resonance frequencies is thus dependent on the frequency resolution Δf. The resolution was here 2 Hz for the longitudinal vibration tests and 0.5 Hz for the bending vibration tests. The maximum relative error (Δf divided by the lowest value for f_1 in the population) for the resonance frequencies of the longitudinal modes is equal to 0.5% (0.3% on average). The corresponding mean values are for the edgewise modes equal to 1.2% and for the torsional modes equal to 0.7%. The overall relative error

Table 1. Raw material properties (standard deviations within parentheses)
Tabelle 1. Eigenschaften des Ausgangsmaterials (Standardabweichung in Klammern)

	Pith [%]	Mean annual ringwidth [mm]	Mean density[1] [kg/m^3]	Mean moisture content[1,2] [%]	Mean density[3] [kg/m^3]	Mean moisture content[3] [%]	Number of specimens [–]
Dim. 38 × 89							
MILL A	76	2,0 (0,8)	503 (45)	16	432 (40)	12,9 (0,6)	29
B	61	2,4 (1,0)	474 (37)	16	411 (36)	11,9 (0,2)	18
C	38	1,8 (0,7)	447 (44)	14	393 (42)	12,3 (0,5)	16
D	81	1,4 (0,5)	466 (29)	14	403 (28)	11,7 (0,2)	16
E	29	2,3 (0,5)	474 (29)	16	416 (32)	12,3 (0,3)	14
F	76	2,5 (1,1)	485 (42)	15	421 (40)	12,2 (0,4)	29
ALL MILLS	*62*	*2,1 (0,9)*	*480 (43)*	*15*	*415 (39)*	*12,3 (0,6)*	*122*
Dim. 38 × 140							
MILL A	50	2,6 (1,1)	499 (42)	17	424 (36)	12,6 (0,6)	30
B	43	3,1 (1,1)	464 (43)	–	410 (37)	12,1 (0,4)	23
C	21	2,0 (1,1)	468 (46)	16	399 (42)	12,7 (0,4)	19
D	25	2,1 (0,5)	435 (37)	15	371 (32)	13,0 (0,3)	16
E	29	2,1 (0,5)	479 (44)	–	417 (40)	12,5 (0,2)	14
F	48	2,9 (1,1)	469 (46)	16	407 (43)	12,1 (0,7)	25
ALL MILLS	*39*	*2,5 (1,1)*	*472 (46)*	*15*	*407 (41)*	*12,5 (0,6)*	*127*
Dim. 38 × 184							
MILL A	20	3,0 (1,0)	461 (49)	20	391 (45)	14,7 (0,7)	50
B	46	2,8 (1,1)	463 (45)	17	396 (51)	13,7 (0,7)	39
C	51	1,5 (0,5)	446 (31)	18	380 (28)	14,2 (0,6)	37
D	21	2,4 (0,8)	424 (29)	16	363 (27)	13,3 (0,6)	48
E	38	2,5 (0,7)	493 (45)	16	423 (41)	14,1 (0,9)	40
F	32	3,1 (1,3)	455 (46)	16	388 (42)	13,4 (0,5)	60
ALL MILLS	*33*	*2,6 (1,1)*	*456 (46)*	*17*	*389 (43)*	*13,9 (0,8)*	*274*
ALL SAMPLES	*41*	2,5 (1,1)	466 (46)	16	400 (43)	13,2 (1,0)	523

[1] Bulk density at the time for the vibration tests.
[2] A few random samples.
[3] Oven dry weight divided by the volume at 12% moisture content.

(worst case) in the determined resonance frequencies was thus at the 1% level.

4.2
Dynamic test results

The dynamic tests resulted in resonance frequencies related to bending, longitudinal and torsional modes of vibration. Resonance frequencies are in general terms proportional to the square root of the ratio between an elastic stiffness and a mass density. The influence on either the elastic stiffness or the mass density from different features of timber can thus be studied by the use of vibration tests. Provided that the mass density of a lumber specimen has been determined, the elastic stiffness can be established. At the time for the dynamic measurements the beam lengths and mass weights were also measured. Based on these measured properties the modulus of elasticity associated with bending and longitudinal extension as well as the shear modulus associated with torsion were determined for each specimen. The moduli were calculated as

$$E_{\mathrm{ew,dyn}} = \frac{f_{\mathrm{ew},1}^2}{3,56^2} \frac{12ML^3}{BH^3} , \qquad (1)$$

$$E_{\mathrm{l,dyn}} = f_{\mathrm{l},1}^2 \frac{4ML}{BH} \text{ and} \qquad (2)$$

$$G_{\mathrm{t,dyn}} = f_{\mathrm{t},1}^2 \frac{ML}{3\kappa_t BH} \left(1 + \frac{B^2}{H^2}\right) . \qquad (3)$$

where $f_{\mathrm{ew},1}$, $f_{\mathrm{l},1}$ and $f_{\mathrm{t},1}$ denote the resonance frequencies of the first edgewise bending, longitudinal and torsional vibration modes respectively. M is the beam mass, L is the length, B is the width, H is the depth and Δt varies nonlinearly from 0.14, for $H/B = 1$, to 0.33 for $H/B \to \infty$. Equations (1), (2) and (3) are valid if the assumptions for the Euler-Bernoulli and St. Venant beam theories are fulfilled.

The results obtained from the vibration tests are displayed in Table 2 as mean values and standard deviations for each timber size and sawmill as well as for the whole population. It was observed that there is a tendency in the results indicating that for larger dimensions the mean values for the E modulus decrease. This holds both for the estimates based on longitudinal vibration and from those evaluated from bending vibrations. The tendency is, in fact, statistically significant on a 4% level. The reason for this tendency could, if only the bending vibrations were measured, be explained by an increased flexibility related to shear deformation with increasing beam depth. But, since the tendency is so pronounced also for the E values determined from the longitudinal modes of vibration, there must be another explanation. The values in Table 1, which displays the raw material properties, show primarily that the deeper the beams are, the lower are the mass density values. The reason for the differences in E modulus and mass density is probably related to how the logs typically are divided into lumber according to Scandinavian practice. When logs are delivered to a sawmill from an arbitrary stand, the population comprises both open-grained and slow-grown wood. The open-grained wood has generally lower values of mass density and mechanical properties than slow-grown wood. The trunks with smaller dimensions are generally more slow-grown than the thicker ones in the same stand. In the log dividing process, the small dimension logs are divided into small dimension lumber and the thicker ones are divided into large dimension lumber. Consequently, the small dimension lumber could be expected to have better mechanical properties than large dimension lumber. This hypothesis is somewhat supported by the mean values of the annual ring widths for the different dimensions given in Table 1; The lumber with smaller cross-section has, on average, more narrow annual rings, which indicate that they originate from more slow-grown trees.

Table 2. Dynamic test results; mean values and standard deviations (within parentheses).
Tabelle 2. Ergebnisse der dynamischen Prüfung; Mittelwerte und Standardabweichung (in Klammern)

	$E_{b,ew}$ [MPa]	E_{ax} [MPa]	G_{to} [MPa]
Dim. 38 × 89			
MILL A	12300 (2200)	12400 (2100)	697 (155)
B	13200 (1900)	13200 (1700)	665 (75)
C	11900 (1900)	11900 (2000)	603 (62)
D	13400 (1400)	13300 (1300)	719 (86)
E	13200 (1100)	13700 (1200)	644 (76)
F	12100 (2600)	12400 (2400)	698 (153)
ALL MILLS	*12600 (2100)*	*12800 (2000)*	*677 (135)*
Dim. 38 × 140			
MILL A	12600 (2700)	12700 (2600)	682 (59)
B	12900 (2100)	12600 (1900)	707 (100)
C	11600 (2500)	11600 (2600)	707 (82)
D	10800 (1700)	11400 (1900)	695 (127)
E	13900 (1800)	13800 (1800)	676 (88)
F	11600 (2300)	11800 (2000)	685 (86)
ALL MILLS	*12200 (2400)*	*12300 (2300)*	*692 (88)*
Dim. 38 × 184			
MILL A	10800 (2200)	11100 (2400)	593 (147)
B	11600 (2200)	11700 (2100)	650 (79)
C	10900 (1500)	11200 (1600)	635 (65)
D	9900 (1800)	10600 (1800)	671 (95)
E	13600 (2200)	13600 (2200)	669 (138)
F	10700 (2300)	11100 (2400)	668 (88)
ALL MILLS	*11100 (2400)*	*11500 (2300)*	*648 (110)*
ALL SAMPLES	*11700 (2400)*	*12000 (2300)*	*665 (112)*

It can also be noted that for the 38 × 184 mm² dimension, the mean E values determined from the longitudinal modes are higher than the ones determined from the bending modes (significance level equal to 4%). The same type of difference is not statistically valid for the smaller dimensions. The relation between the edgewise and the longitudinal E modulus for the 184 mm deep beams is also illustrated in Fig. 1, where the regression line has been forced to pass through the origin. Ohlsson and Perstorper (1992) have shown, for a timber beam of Norway spruce (E/G can be assumed to be of a constant order of magnitude for this species) that the shear deformations and rotary inertia of the cross-section start to play a significant role for the bending mode resonance frequencies when the relative nodal distance (RND) is, say, less than 15. The RND is defined as the shortest distance between nodal points for a bending mode divided by the beam depth. The RND for the 38 × 184 beams was in relation to the first edgewise bending mode approximately equal to 12 (for the shortest specimens), while the RND was around 20 for the shortest 38 × 89 beams. It can thus be expected that the flexibility associated with shear deformation and the rotary inertia, which are present in a bent beam with a nonuniform moment distribution, influence on the resonance frequencies of the bending modes for the 38 × 184 dimensions but not significantly for the other sizes.

The existence of the pith within a specimen is another parameter that could influence the mechanical timber

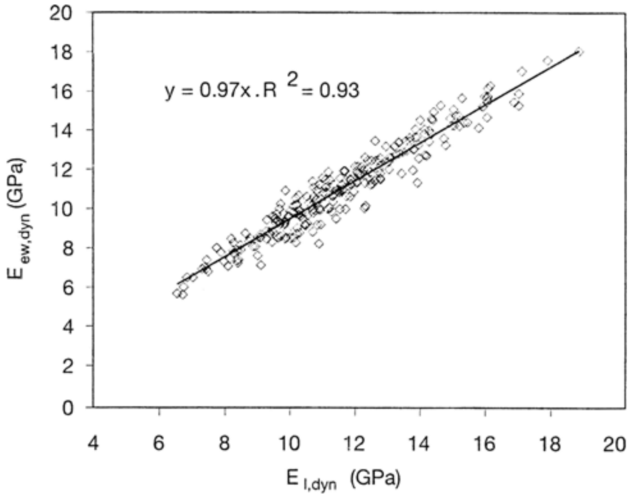

Fig. 1. The relation between two dynamic E moduli, determined from edgewise bending ($E_{ew.dyn}$) and longitudinal ($E_{l,dyn}$) modes of vibration, for the 184 mm deep beams
Bild 1. Beziehung zwischen zwei Prüfverfahren für den dynamischen E-Modul ($E_{ew.dyn}$) und ($E_{l,dyn}$) für Balken mit 184 mm Tiefe

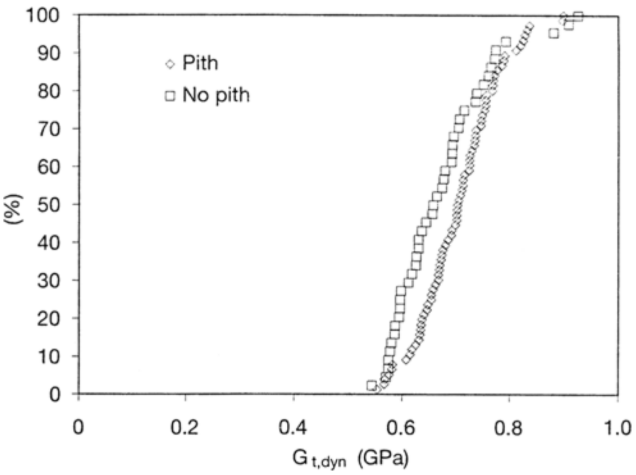

Fig. 2. Cumulative distributions, for the 89 mm deep beams with and without the pith, with respect to the torsional shear modulus $G_{t,dyn}$
Bild 2. Kumulative Verteilungen der Schermoduls ($G_{t,dyn}$) für Balken von 89 mm Tiefe mit und ohne Markanteil

properties. It is generally accepted that the splint of Norway spruce logs has a higher bending strength and *E* modulus than the pith, which is believed to be caused by differences on a cellular level.

A statistical *t*-test (Students' test) gave that the elastic constants were on average different for lumber that comprises the pith compared to lumber sawn radially further out in the log. Table 3 shows the tendency of the differences and to what extent, in a statistical sense, there is a difference or not. It is observed that the *E* modulus is on average lower closer to the pith while for the shear modulus the contrary is true; the shear modulus is higher closer to the pith. As can be seen in Table 3, the levels of significance differ between the lumber sizes. For the 38 × 184 specimens, one cannot state that there is a difference between the shear modulus for lumber taken close to the pith compared to lumber taken further out in the log, while the corresponding difference for the 38 × 89 lumber is significant (5% level). A cumulative graph that illustrates the differences in shear modulus values between 38 × 89 lumber with and without the pith is shown in Fig. 2.

5
Static tests

5.1
Test procedure

Each lumber specimen was tested with a four-point loading test. The distances between the loads varied with the beam depth. The total span was equal to 1602 mm for the 89 mm deep beams, while the distance between the loading heads was equal to 560 mm. The corresponding distances for the 140 mm deep beams were equal to 2520 mm and 860 mm, and for the 184 mm deep beams equal to 3312 mm and 1160 mm. The rate of loading was controlled by a chosen deflection rate of 7 mm/min. The time to failure was on average 4 min., 5.5 min. and 6 min. for the 89 mm, 140 mm and 184 mm deep beams, respectively. The measured deflections that were the basis for establishing the *E* modulus were taken as the deflection of a rigid yoke that carried the loading heads. Such a procedure is convenient to perform, although there is a certain risk for overestimation of the deflections due to local crushing of the wood fibres perpendicular to grain, where the loads were applied. The moisture content of each specimen was found in the range 12% to 14%, see Table 1.

5.2
Test results

The results of the static tests are given as mean values and standard deviations in Table 4 as function of the different sizes and sawmill batches. The *E* modulus of the 184 mm deep beams is significantly lower than the *E* values for the 89 mm and 140 mm deep beams for which there is no significant difference. The tendency to that deeper beams show lower *E* values is valid but weaker compared to the dynamic test results. The established strength values show, however, that there is a distinct depth effect on the bending

Table 3. The pith influence on dynamically determined elastic constants
Tabelle 3. Einfluß des Markanteils auf die dynamsich ermittelten Konstanten

	Pith		No pith		Students' test, sign. level [%]
	Mean [MPa]	s [MPa]	Mean [MPa]	s [MPa]	
$E_{lo,dyn}$ (38 × 89)	12600	2100	13000	1800	*(13)*
$E_{lo,dyn}$ (38 × 140)	11700	2200	12700	2300	1
$E_{lo,dyn}$ (38 × 184)	11000	1900	11800	2400	0,1
$E_{ew,dyn}$ (38 × 89)	12500	2200	12800	1700	*(22)*
$E_{ew,dyn}$ (38 × 140)	11900	2500	12500	2400	8
$E_{we,dyn}$ (38 × 184)	10800	2000	11300	2500	5
$G_{to,dyn}$ (38 × 89)	710	75	670	90	3
$G_{to,dyn}$ (38 × 140)	710	100	680	80	7
$G_{to,dyn}$ (38 × 184)	650	80	660	90	*(32)*

Table 4. Static test results; mean values and standard deviations (within parentheses)
Tabelle 4. Ergebnisse der statischen Prüfung, Mittelwerte und Standardabweichungen (in Klammern)

	$E_{ew,st}$ [MPa]	f_m [MPa]
Dim. 38 × 89		
MILL A	10300 (2300)	42,9 (17,4)
B	11500 (1300)	54,2 (7,9)
C	10900 (1700)	54,6 (14,2)
D	11400 (1200)	58,5 (12,1)
E	11600 (1400)	59,2 (9,6)
F	10500 (2400)	48,0 (17,1)
ALL MILLS	*10900 (1900)*	*51,3 (15,1)*
Dim. 38 × 140		
MILL A	11800 (2700)	44,2 (15,6)
B	11400 (2400)	46,7 (14,4)
C	10500 (2300)	46,1 (15,2)
D	9800 (1700)	44,4 (12,3)
E	12600 (1900)	53,5 (12,3)
F	10800 (1800)	41,1 (12,6)
ALL MILLS	*11200 (2300)*	*45,4 (14,2)*
Dim. 38 × 184		
MILL A	9700 (2000)	35,2 (9,0)
B	10500 (2300)	38,1 (7,3)
C	10100 (1300)	38,6 (5,3)
D	9000 (1500)	33,9 (8,5)
E	12600 (2000)	44,0 (7,4)
F	9800 (2500)	34,2 (10,9)
ALL MILLS	*10200 (2300)*	*36,9 (9,1)*
ALL SAMPLES	10600 (2300)	*42,4 (13,5)*

strength. The bending strength values of the 89 mm deep beams are on average 40% higher than for the 184 mm deep beams. The pith influence on the static properties is illustrated by the figures in Table 5. It is clear that lumber sawn close to the pith of the tree shows a lower strength and is more flexible in bending compared to beams sawn further out in the log. The "pith effect" is also illustrated in Fig. 3 for the 89 mm deep beams. The symbols that represent the pith values form a somewhat discontinuous curve. When the data were sorted in ascending order, the values were somewhat grouped with respect to the lumber origin (mills). There is, however, no significant trend to that a certain mill is found among the lower values of the "pith data". One can thus say that there is a difference in mechanical properties between lumber sawn close to the pith when compared to lumber without the pith.

6 Comparison between dynamically and statically determined mechanical properties

The mechanical properties determined both from the dynamic and static tests, for which mean values and standard deviations were presented in previous sections, will be compared and discussed here. By comparing the values in

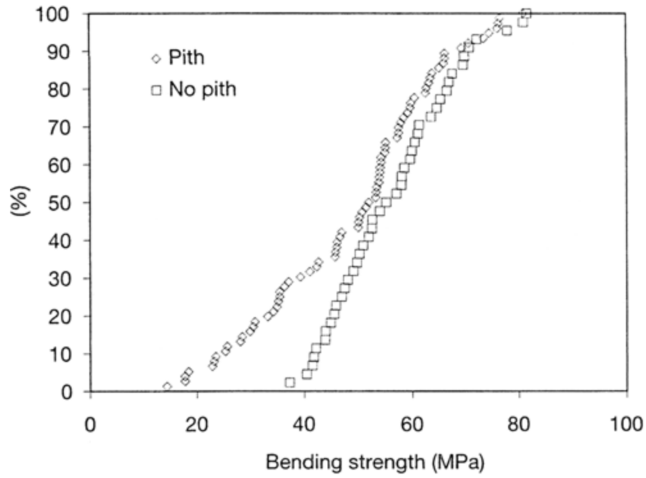

Fig. 3. Cumulative distributions, for the 89 mm deep beams with and without the pith, with respect to the bending strength.
Bild 3. Kumulative Verteilungen der Biegefestigkeit für Balken von 89 mm Tiefe mit und ohne Markanteil

Tables 2 and 4 it can be observed that the dynamic E values are on average higher than the static ones. The ratio $E_{ew,dyn}/E_{ew,st}$ is approximately equal to 1.10 and the ratio $E_{l,dyn}/E_{ew,st}$ is equal to 1.13 for the whole population. The differences can probably be explained by two factors. The first one is related to the static test procedure, which was previously commented upon. The second factor is, as many researchers have indicated, related to the viscoelastic nature of wood. During the static tests, which lasted here for about 5 minutes, creep effects will influence on the measured static deflections.

The direct comparison between the edgewise E modulus established from dynamic testing and the corresponding static E-modulus is illustrated in Fig. 4. Regression lines are given in Table 6 for that relation and others. The correlation between $E_{ew,dyn}$ and $E_{ew,st}$, and $E_{l,dyn}$ and $E_{ew,st}$ are strong for the 140 mm and 184 mm deep beams. The relation is weaker for the 89 mm deep beams, which is also displayed by the diverging regression lines in Fig. 4.

The similar observations as were made between E modulus values can be made with respect to the E modulus (independently of measurement method) and the bending strength.

The correlation between the edgewise dynamic E modulus and the bending strength is shown in Fig. 5, where the previously mentioned depth influence on the apparent bending strength is clearly illustrated by the separated regression lines.

7 Comparisons between mechanical and physical properties

At the time for the static tests, annual ring widths and mass densities were determined for all samples. It is of

Table 5. The pith influence on statically determined properties
Tabelle 5. Einfluß des Markanteils auf die statisch ermittelten Eigenschaften

	Pith		No pith		Students' test, sign. level [%]
	Mean [MPa]	s [MPa]	Mean [MPa]	s [MPa]	
$E_{ew,st}$ (38 × 89)	10600	2100	11300	1600	3
$E_{ew,st}$ (38 × 140)	10800	2500	11400	2200	8
$E_{ew,st}$ (38 × 184)	10000	2000	10300	2400	*(13)*
f_m (38 × 89)	49	16	55	12	2
f_m (38 × 140)	42	16	48	13	2
f_m (38 × 184)	36	9	37	9	*(15)*

Table 6. Regression equations, coefficients of determination and standard deviations for the residuals between the predicted and measured mechanical properties

Tabelle 6. Regressionsgleichungen, Bestimmungsmaße und Standardabweichungen für die Differenzen zwischen vorhergesagten und gemessenen mechanischen Eigenschaften

Size [mm^2]	Regression equation [MPa]	R^2	StdDev of residual [MPa]
Elastic constants			
38 × 89	$E_{ew,st} = E_{lo,dyn} \times 0{,}81 + 610$	0,68	1090
	$E_{ew,st} = E_{ew,dyn} \times 0{,}78 + 1050$	0,70	1060
38 × 140	$E_{ew,st} = E_{lo,dyn} \times 0{,}96–641$	0,91	720
	$E_{ew,st} = E_{ew,dyn} \times 0{,}90+188$	0,89	793
38 × 184	$E_{ew,st} = E_{lo,dyn} \times 0{,}90–159$	0,83	945
	$E_{ew,st} = E_{ew,dyn} \times 0{,}90+201$	0,86	855
Elastic constants & bending strength			
38 × 89	$f_m = E_{ew,st} \times 0{,}0054–7{,}3$	0,47	11,0
	$f_m = E_{lo,dyn} \times 0{,}0049–11{,}7$	0,42	11,6
	$f_m = E_{ew,dyn} \times 0{,}0045$ 5,9	0,39	11,9
38 × 140	$f_m = E_{ew,st} \times 0{,}0048–7{,}8$	0,61	8,9
	$f_m = E_{lo,dyn} \times 0{,}0048-13{,}5$	0,63	8,7
	$f_m = E_{ew,dyn} \times 0{,}0047$ 11,5	0,61	9,0
38 × 184	$f_m = E_{ew,st} \times 0{,}0030 + 6{,}2$	0,56	6,1
	$f_m = E_{lo,dyn} \times 0{,}0030 + 3{,}9$	0,56	6,1
	$f_m = E_{ew,dyn} \times 0{,}0030$ 2,7	0,58	5,9

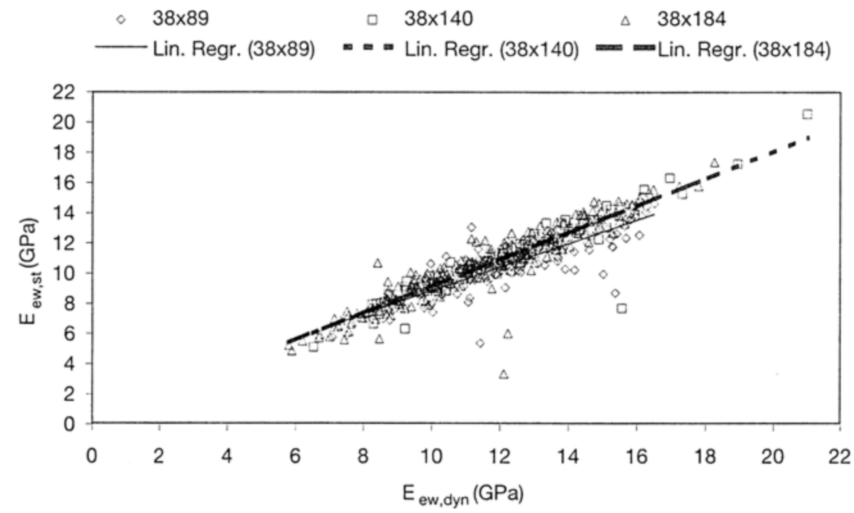

Fig. 4. The relation between edgewise dynamic ($E_{ew,dyn}$) and static ($E_{ew,st}$) E moduli
Bild 4. Beziehung zwischen dynamischem ($E_{ew,dyn}$) und statischem ($E_{ew,st}$) E-Moduli

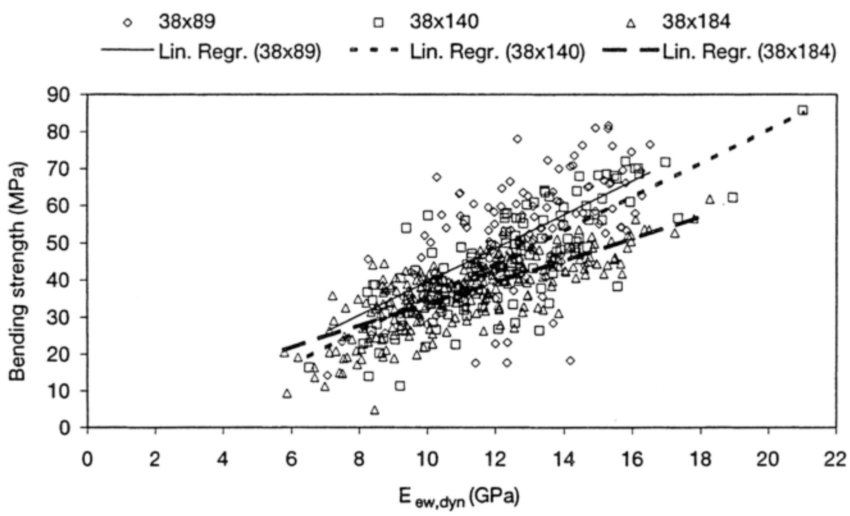

Fig. 5. The relation between edgewise dynamic E modulus ($E_{ew,dyn}$) and bending strength
Bild 5. Beziehung zwischen dynamischem E-Modul ($E_{ew,dyn}$) und Biegefestigkeit

interest to see to what extent these physical properties can be used for the explanation of the mechanical properties of lumber. Figure 6 illustrates one such example (for the 184 mm deep beams), where the $E_{l,dyn}$ is plotted as function of annual ring width (RW). One can see that there is a very weak tendency to that the wider the rings are the more flexible is the lumber. The annual ring width is thus not a good measure neither for stiffness nor for bending strength of structural timber, compare Fig. 7.

One could argue that it is not the ring width itself that is governing for the stiffness and strength, but rather the amount of earlywood compared to latewood. The cells of

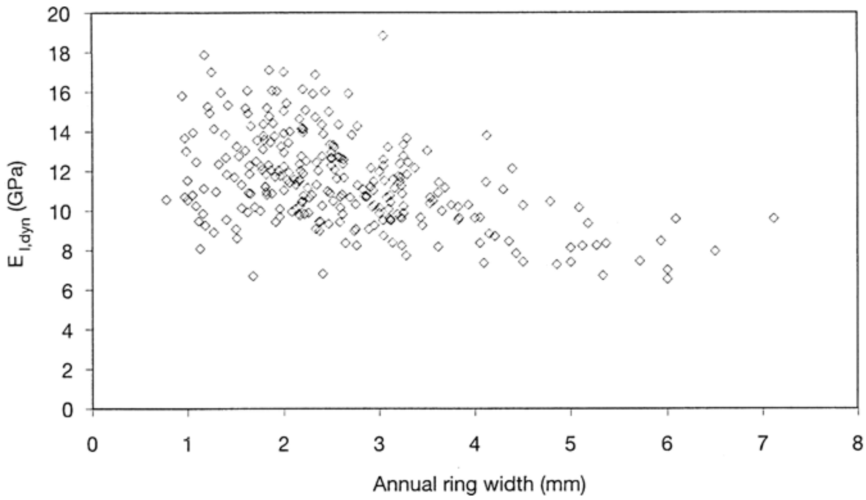

Fig. 6. The relation between longitudinal dynamic E modulus ($E_{l,dyn}$) and the annual ring width for the 184 mm deep beams
Bild 6. Beziehung zwischen dynamischem E-Modul ($E_{l,dyn}$) und Jahrringbreite für Balken mit 184 mm Tiefe

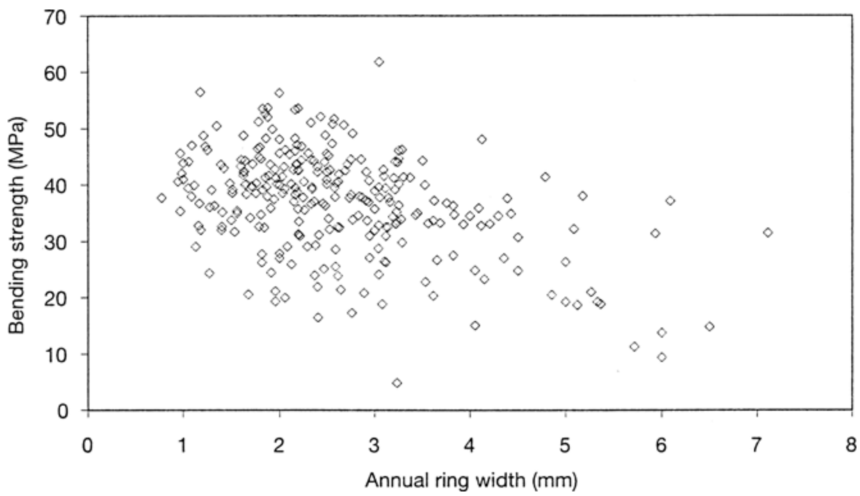

Fig. 7. Bending strength as a function of the annual ring width for the 184 mm deep beams
Bild 7. Biegefestigkeit in Abhängigkeit von der Jahrringbreite in Balken mit 184 mm Tiefe

the earlywood are known to have thicker walls; the amount of cellulose molecules are higher than for the latewood. A higher concentration of cellulose chains leads to that the earlywood is heavier, stiffer and stronger than the latewood. The mass density could thus be a potential indicator of the timber stiffness and strength. Figure 8 shows a diagram for $E_{ew,st}$ as function of mass density (mass at 12% moisture content divided by the oven-dry volume) for the 184 mm deep beams. A certain correlation between the parameters is evident, but it is not very strong. In fact, the correlation gets weaker for the lumber of smaller size. The relation between mass density and bending strength is illustrated in Figure 9. A good correlation between these parameters can hardly be said to exist and the correlation is even weaker for the small dimension lumber.

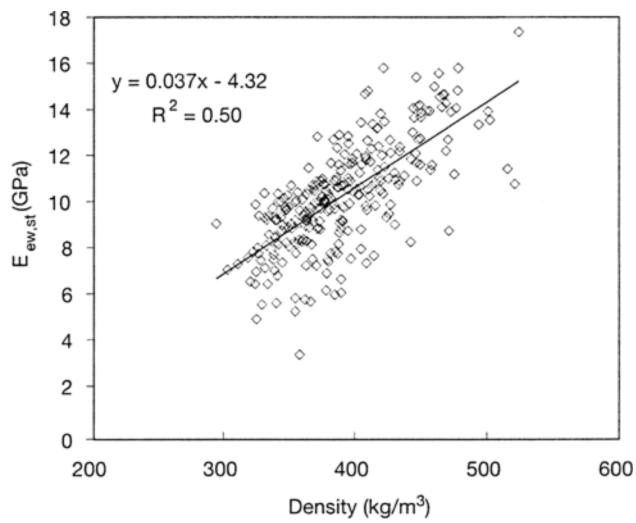

Fig. 8. The relation between edgewise static E modulus ($E_{ew,st}$) and density for the 184 mm deep beams
Bild 8. Beziehung zwischen statischem E-Modul ($E_{ew,st}$) und der Rohdichte für Balken mit 184 mm Tiefe

8
Concluding remarks

A number of conclusions can be drawn from the results in this study. Two types of observation will be discussed. The first one relates to whether or not the values of the dynamic and static E modulus reflect the same stiffness. The other type concerns the material characteristics as such.

Dynamically established values for the E modulus were on average found to be about 10% higher than the static ones. The coefficient of determination for the correlation between static and dynamic E modulus was high; It varied between 0.70 and 0.90 for different cross-sectional sizes. The lower value is related to the tests of lumber with cross sections of 38×89 mm^2. The E modulus has for a long time been taken as a predictor of the bending strength of structural timber. Statistical correlation between E modulus and bending strength for the material tested, yielded

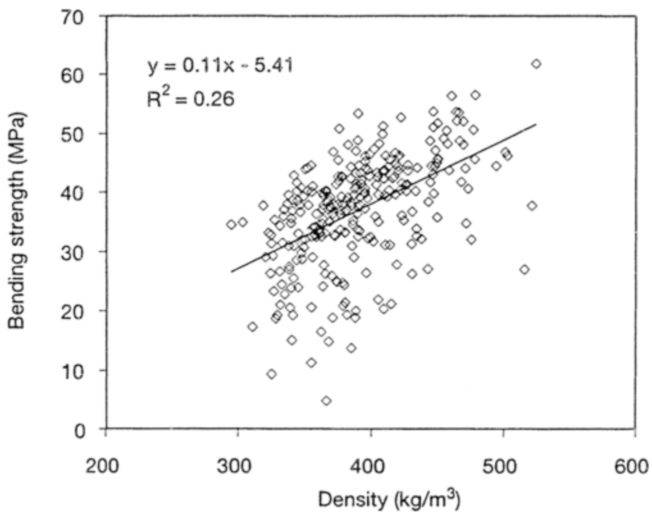

Fig. 9. The relation between bending strength and density for the 184 mm deep beams
Bild 9. Beziehung zwischen Biegefestigkeit und Rohdichte für Balken mit 184 mm Tiefe

values for the coefficient of determination (R^2 values) of the same order of size; $R^2 = 0.4$–0.5 for the 89 mm deep beams, and $R^2 \approx 0.6$ for the 140 mm and 184 mm deep beams. It can be concluded that the E modulus established both from edgewise bending modes and longitudinal modes is well correlated to the E modulus obtained from static tests and that it is also statistically correlated to the bending strength.

A total number of 525 tested timber beams, which were taken from six different saw mills and represented three different dimensions, were included in the batch. From the dynamic tests it was observed that the larger the lumber size is the lower the E modulus is. The reason for this tendency is believed to be dependent on how the logs typically are divided into lumber; A slow-grown tree has generally better mechanical properties than a fast-grown tree in the same stand. The larger fast-grown trees will naturally be divided into lumber of larger sizes. In addition, the bending strength of the deepest beams ($h = 184$ mm) was lower than for the 89 mm deep beams. Apart from the log dividing process, another plausible reason for the size dependence of the strength is that there is a volumetric effect on the bending strength related to the failure mechanism, c.f. Foschi et al. (1989).

For the 184 mm deep beams it was also observed that the E modulus established from longitudinal vibration modes was significantly higher than the E modulus established from bending vibration modes. The difference is caused by that shear deformations and rotary inertia of the cross sections start to play a role on the bending behaviour for deeper beams.

The inclusion or exclusion of the pith in the lumber has an effect on the mechanical properties, although it is not always significantly palpable for the structural timber here. Both with respect to dynamically and statically determined values of the E modulus, it was shown that lumber that does not contain the pith, is stiffer than lumber that contains the pith. The same relation is valid for the bending strength; higher strength values for lumber sawn radially further out in the stem. The contrary tendency was found for the shear modulus; lumber sawn close to the pith shows higher values of the shear modulus.

Average values for the mechanical properties of the whole batch of lumber were as follows. The modulus of elasticity established from the vibration tests were equal to 11700 MPa (edgewise bending) and from the static tests equal to 10600 MPa. The shear modulus determined from torsional vibration modes was equal to 660 MPa. The bending strength was equal to 42 MPa.

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