

The development of a strength grading system for small diameter roundwood

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Roundwood as a construction material is becoming more and more interesting to users. Using this wood in construction will increase the value of the material and may open new opportunities for construction design. In order to use roundwood for this application, suitable connectors and/or joints have to be developed, but before all, the strength characteristics of roundwood must be determined and grading systems should be established. This investigation deals with the determination of the modulus of elasticity and the bending strength. The wood species concerned are Larch, grown in The Netherlands, and Douglas fir, grown in France, with diameters between 80 mm and 140 mm. The modulus of elasticity is determined by static and dynamic test methods. The data were included in a multiple regression model in order to predict the bending strength. The resulting model is compared with models for sawn timber that are nowadays used in practice.

Key words: roundwood, strength grading, testing

1 Introduction

Small diameter round poles are obtained in large quantities from thinnings. Presently the use of this material is not optimised in terms of commercial value, it is chipped for the panel industry, used as firewood or not even harvested from the forest site. Current EC research investigates the possibilities of structural systems in which small diameter (80–150 mm) roundwood is used. Structural applications will increase the value of this wood.

The main issue that has to be dealt with in order to introduce roundwood on the building material market is the adjustment of the image that building industry has of small round poles. Both wood industry, designers and building control authorities are presently unacquainted with and consequently reserved about the possibilities of thin poles as building material. Research therefore first aims at laying down the quality of the material and at the demonstration of its potentiality by the actual construction of load bearing structures.

In line with sawn timber, roundwood for construction purposes also has to be sorted according to strength classes. For sawn timber, existing European Standards describe testing methods (EN 408

[4]), procedures to calculate characteristic values (EN 384 [12]), grading rules and strength classes (EN 338 [1]). For roundwood however, no grading system exists which links material characteristics to strength values. The development of such a system is one of the main tasks of the EC project "Small diameter roundwood for constructions (FAIR CT-95-0091)" in which among others research groups from Centre Technique du Bois et de l'Ameublement (CTBA) and Delft University of Technology (DUT) are involved.

To put a first step in the development process of a roundwood grading system, the sawn timber system (Figure 1) is used as a basis. Since the geometry and material composition of small round poles differ significantly from regular sawn timber sections, all procedures this grading system comprises (testing methods, determination of characteristic values, grading parameters, strength class classification) need to be judged upon their validity and usefulness in a practical strength grading system for roundwood.

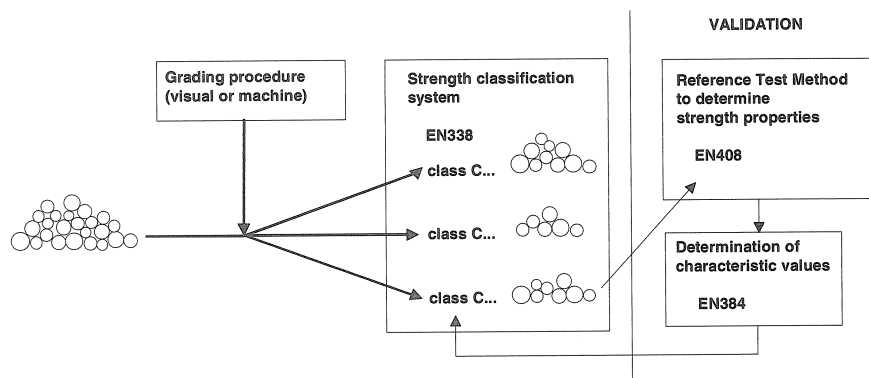


Fig. 1. Elements of grading system.

This paper concentrates on the (reference) test methods to determine the Modulus of Elasticity (E_m) and on the potentiality of E_m as a grading parameter with respect to strength class classification.

2 Grading methods

For sawn timber both visual and machine strength grading systems are established in the wood industry. Reasonable relationships are found between the Modulus of Elasticity, some visual features (e.g. knots) and the bending strength (Modulus of Rupture, f_m).

The quality of a grading system can be assessed on requirements which are related to the industrial use of the timber. For example: If a company needs only timber of strength classes C18, C22 and C24 then the grading system has to be able to optimise the yield for these classes. In this case it is not necessary that the system is able to distinct timber which belongs in strength classes higher than C24. Also the costs of a grading system has to be considered and be related to the benefit of the results.

Currently roundwood is not a high value building material, consequently grading procedures have to be simple and low cost level.

2.1 Visual strength grading

In principle every visible timber property or feature is suitable for strength grading, provided there exists a relation between this property and the strength and stiffness. Examples are slope of grain, annual ring width, knots, wane, distortions or decay caused by micro-organism.

Grading rules that limit visible properties enable the prediction of the strength of a piece of timber based on established relations between visible features and the member strength. Visual strength grading is therefore defined as classifying timber according to its strength, based on statistical relations between visible features and the load-carrying capacity.

There are some disadvantages of visual grading [2]:

- It is impossible to write a set of grading rules covering all the complexities and combinations of strength reducing features of a piece of timber.
- Some properties closely related to the strength are hardly to assess by visual inspection.
- Relatively weak relation between the measured parameters and the strength of a piece of timber. e.g. correlation (r -value) factors (sawn timber) for knots about 0.5, ring width 0.4 [5].

2.2 Machine strength grading

Closer relations between strength and grading parameters produce a lower variation within a timber grade and consequently give better grade recoveries over visual grading. Most of the machines used for grading sawn timber are based on stiffness measurements, using the close relationship between the stiffness or modulus of elasticity of a piece of timber and its strength. The correlation between Modulus of Elasticity and Modulus of Rupture is about 0.7–0.8 (r -value) for sawn timber. Most of the machine graded timber today is graded using bending machines. The timber is loaded by a central load while the piece of timber is deformed. From the deformation, the load and the cross sectional dimensions the modulus of elasticity as the grading parameter is calculated.

Another principle of measuring the stiffness of timber is based on the relationship between the frequency of a freely vibrating piece of timber and its modulus of elasticity [3]. Vibration measurements are more reliable than in line deformation measurements and can be used for cross sectional dimensions that vary along the length of the test piece.

3 Materials

The specimens used for the investigation were Larch (*Larix kaempferi* (LAMB.) CARR.) grown in the eastern area of the Netherlands and Douglas (*Pseudotsuga menziesii* (Mirb.) Franco) from France. From Larch about 220 specimens were selected and tested. A number of 108 cylindrical milled specimens and 29 only debarked, kept in the tapered shape, were used in this investigation. From Douglas a great number of specimens were tested but in this analyses 145 specimens were used (Table 1).

Table 1. Specimens involved.

Diameter test piece [mm]	number	Length specimen [mm]	Length test piece [mm]	tree age [years]	taper [mm/m]
<i>Larch</i>					
100	40	3500	2200	40 ± 6	
120	30	4000	2600	42 ± 5	
140	38	4500	3000	45 ± 4	
tapered 120-140	29	4500	3000	35 ± 6	5 ± 2
<i>Douglas</i>					
80	69	4000	1600		
120	76	4000	2400		

After machining, the poles were transported to the institutes and dried by conditioning at ca. 65% RH and ca. 18°C. The moisture content (MC) at testing was for Larch about 15% and for Douglas about 11%. After drying most of the specimens were cracked along the grain. The width of the crack varies between 3 mm and 15 mm.

4 Methods

In this paragraph methods are described to determine grading characteristics as well test methods which are used as reference to determine the Modulus of Elasticity (Figure 2).

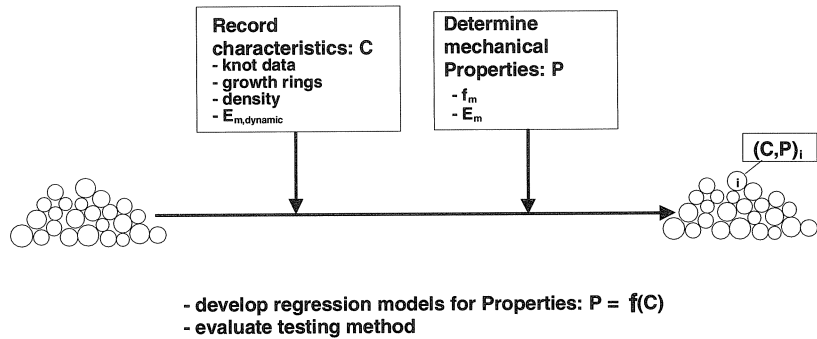


Fig. 2. Conducted characterizations and tests.

4.1 Visual grading parameters

To predict the strength of the specimens the following visual features of the test specimens were determined: knottiness, ring width and density. For the specimens from Larch the features were determined as followed:

- The density was calculated by measurement of the test piece dimensions, mass, crack width and moisture content.
- Knottness was expressed as the quotient of the test piece maximum knot diameter and the diameter of the specimen.
- Growth rings data was expected to be an important parameter in the quality characterisation for round wood. The composition, width and number of the growth rings give information on the share of juvenile wood and the age of the specimens.

The following aspects were recorded (Figure 3):

- the maximum number of complete growth rings and the accompanying width in mm ($N_{max} R_{max}$)
- the number of rings in the first 20 mm from the pith (N_{20})

Using these data the following growth ring characteristic was calculated:

$$RWC_{max} = (R_{max} - 20) / (N_{max} - N_{20}) \text{ [mm/year]}.$$

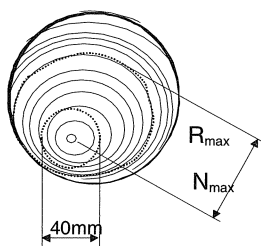


Fig. 3. Growth ring determination.

4.2 Dynamic Modulus of Elasticity ($E_{m, dyn}$) as grading parameter

A relatively cheap and quick way of measuring the stiffness of timber is based on the relationship between the eigenfrequency for free-free condition of a specimen and its elasticity. A lot of research work is already done [7], [8], [9], [10]. This method is based on the Euler beam theory for free flexural vibrations of prismatic beams. The eigenfrequency of a material is the basis vibration of the whole specimen at normal mode. The vibration can be initiated by a longitudinal or a transverse impact. Due to the geometry and mass of the samples and test arrangement considered, the longitudinal vibration method was applied. Longitudinal vibrations of beams with small cross-sections with respect to length are not significantly influenced by shear and torsional deformations.

The fundamental relationship is given by the differential equation (1)

$$\rho \frac{\partial^2 u}{\partial t^2} = E \frac{\partial^2 u}{\partial x^2} \quad (1)$$

- u Longitudinal displacement
- x Distance along the beam
- ρ Density
- E Modulus of elasticity

Assuming ρ and E to be constant equation (2) can be derived:

$$u = \left[C_1 \cdot \sin \left(\frac{\omega x}{\sqrt{\frac{E}{\rho}}} \right) + C_2 \cdot \cos \left(\frac{\omega x}{\sqrt{\frac{E}{\rho}}} \right) \right] \cdot \cos(\omega t) \quad (2)$$

In case that both ends of the beam are free, means $u' = 0$ at $x = 0$ then C_1 becomes zero. Substituting ω by $2\pi t$ equation (3) can be derived:

$$f = \frac{\sqrt{\frac{E}{\rho}}}{2 \cdot l} \cdot n \quad (3)$$

f Frequency

n Mode

From equation (4) the Modulus of Elasticity can be calculated.

$$E_{\text{mdyn}} = 4l^2 f^2 \rho \quad (4)$$

E_{mdyn} Modulus of elasticity dynamic

l Length of the specimen

f Frequency

ρ Specific gravity

High correlation between $E_{\text{m dyn}}$ and $E_{\text{m stat}}$ are established for sawn timber ($r=0.93$) on laboratory scale [7]. When applying the vibration method under industrial conditions the correlation coefficient obtained is lower [2], [11].

The vibration was initiated by a longitudinal impact (Figure 4). The acceleration was measured by a Piezo-electrical transducer. The applied device is called GrindoSonic MK5 "industrial".

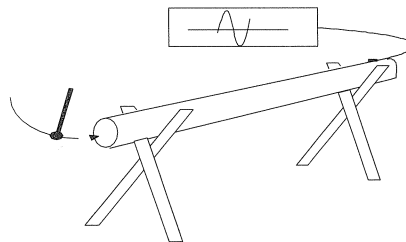


Fig. 4. $E_{\text{m dyn}}$ test arrangement.

4.3 Reference test methods for Modulus of Elasticity

A key element in a strength grading system is a reference testing method to determine f_m en E_m . For the design of the test arrangement, basically the standard EN 408 for sawn timber was used. As round poles differ in many ways from sawn timber, practical problems were expected to arise:

- Roundwood poles normally have some initial curvature and specially wood that is only debarked will have an elliptical shaped cross section. The curvature may force special positioning of a pole in the test arrangement. This means it is not possible to measure the relevant cross section dimensions for the calculation of the moment of inertia until after the pole is placed in the test bench.
- Clearly some cross section dimension will have to be defined to determine span length, moment of inertia and limits of the deformation speed. Diameter ranges can be used for span and speed, but exact cross section dimensions are necessary for the moment of inertia (I).
- When using external devices to measure displacements special attention should be paid to rotations of the test piece during loading.
- The irregular and cracked surface can cause problems when mounting displacement measurement reference points at prescribed positions.
- The load should be applied in the neutral plane of a pole. This means tapered poles cause the use of special loading heads that can easily be adjusted to accommodate various diameters.

Essentially evaluation of the testing method meant the analysis of the impact of these problems on the accuracy of the test results. In both CTBA and DUT laboratories a test arrangement was built, according to the EN 408 description for the testing of sawn timber. To be able to investigate the accuracy of the results, for each specimen two values for the modulus of elasticity were measured simultaneously, a local (as described in EN 408) and a total value.

In the EN 408 experiment (Figure 6) only local specimen characteristics (knots and density of the middle 6D section of a test piece) and E_m influence the force-deflection graph. From this the $E_{m\text{ local}}$ is determined.

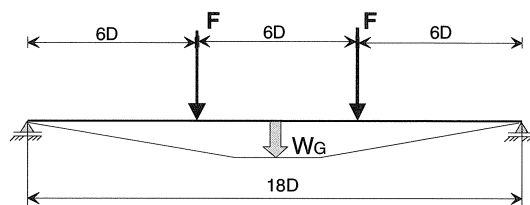


Fig. 5. $E_{m\text{ stat total}}$ deflection measurement.

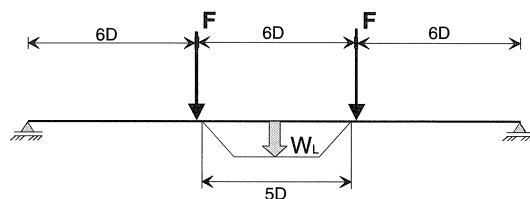


Fig. 6. $E_{m\text{ stat total}}$ deflection measurement.

The total value ($E_{m\text{ total}}$) was measured by recording the displacement of the specimen middle section with respect to the end supports. (Figure 5 W_G). In this experiment the force-deflection relation is influenced by the full specimen's characteristics, E_m and the shear modulus (G).

With the EN 408 span lengths and a shear modulus value $G = E/16$, the theoretical relative difference between $E_{m\text{ stat local}}$ and $E_{m\text{ stat total}}$: $(RD_{tl} = (E_{m\text{ stat local}} - E_{m\text{ stat total}}) / E_{m\text{ stat local}})$ can be calculated. RD_{tl} values (mean, distribution) of a test series can be checked against this. The RD_{tl} values can be seen as characteristics of the test arrangement, they are independent of the test material. Results from different test arrangements should yield comparable RD_{tl} values.

To implement the test arrangement at DUT laboratories a Instron model 1195 loading frame was extended with a 3.5 meter long I-beam. On this beam two end supports were attached so that various specimen lengths could be tested (Figure 7). Linear Variable Displacement Transducers (LVDT's) were used to measure the deflections.

The design of the loading heads enabled both rotation of the loaded sections and translation of the test piece surface during the experiment. The axis of rotation of the loading heads lies inside the neutral plane of the specimen.

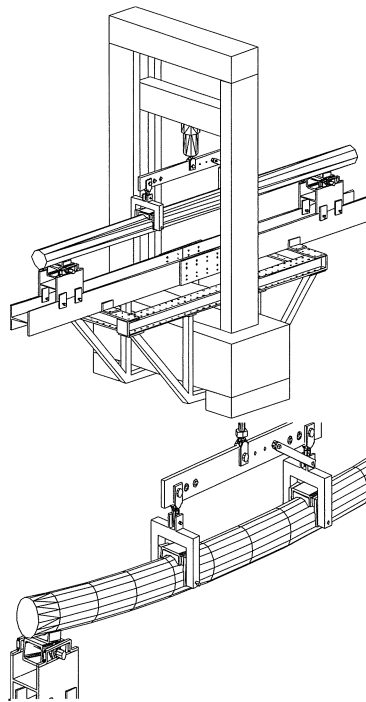


Fig. 7. Test arrangement.

To carry out the measurements of the displacements according to EN 408 prescription, three reference points were attached to a specimen. On the two outer reference points a frame with the LVDT was mounted (Figure 8). The LVDT core was placed on a flat horizontal plane that could rotate free around the centre reference points axis. Special LVDT configurations were used to control accurate measurement of the deflections. For both local and global measurements two LVDT's (Figure 9; local: A and B, global: C2 and C1) were used to adjust for possible rotation of the specimen during the experiment.

The maximal force applied during the Modulus of Elasticity experiment was 40% of the expected failure load (F_{MAX}) of the specimen. F_{MAX} was determined by a small Modulus of Rupture test series for each diameter group. Loading speed was 2mm/min and calculation of slope of the deformation graph was done by linear regression on the force – displacement measurements in the loading area between 10% and 40% of F_{MAX} .

After the Modulus of Elasticity experiment the poles were relieved and again loaded to failure to determine the bending strength. In order to reach the failure load within the EN408 time-span, the deformation speed during the Modulus of Rupture experiment was 10 or 20 mm/min (depending on the pole diameter).

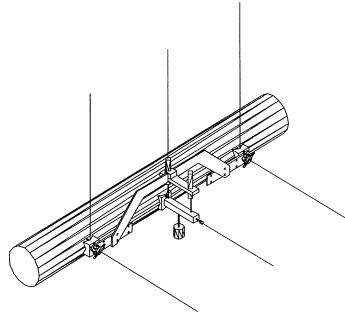


Fig. 8. Measurement of EN 408 deflection.

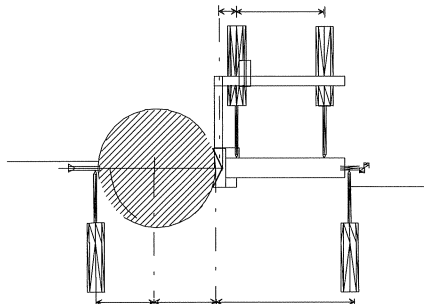


Fig. 9. Local (A) and total (C1, C2) LVDT placements.

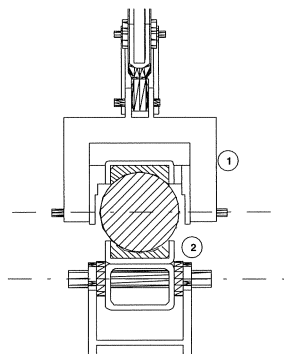


Fig. 10. Loading heads cross section.

5 Results

5.1 Predicting Modulus of Rupture (f_m)

In order to come to a strength grading system, the determined features and properties (see paragraph 4) are correlated with f_m . The results for Larch are presented in Table 2.

Table 2. Correlation coefficients (r) between significant parameters for Larch.

	f_m	ρ_0	$E_{m \text{ dyn}}$	$E_{m \text{ stat total}}$	$E_{m \text{ stat local}}$	knot value	growth ring value
f_m	1.00						
ρ_0	0.65	1.00					
$E_{m \text{ dyn}}$	0.76	0.75	1.00				
$E_{m \text{ stat total}}$	0.76	0.66	0.85	1.00			
$E_{m \text{ stat local}}$	0.72	0.64	0.82	0.91	1.00		
knot value	-0.64	-0.45	-0.61	-0.56	-0.53	1.00	
growth ring value	-0.56	-0.34	-0.52	-0.52	-0.43	0.55	1.00

Table 2 shows the strongest single correlation between f_m and the material properties that were taken into account, is obtained by $E_{m \text{ dyn}}$ and $E_{m \text{ stat total}}$. This correlation value can be improved by applying multiple regression analyses. The results are shown in Table 3. In the models the different parameters are considered which where marked in.

Table 3. Correlation coefficients (r) between f_m and parameters involved in the model.

model	correlation coefficient (r)	model parameters				
		$E_{m \text{ dyn}}$	$E_{m \text{ stat total}}$	density	knots	growth ring
1	0.76	x				
2	0.77	x		x		
3	0.79	x			x	
4	0.79	x				x
5	0.76		x			
6	0.79		x	x		
7	0.80		x		x	
8	0.79		x			x
9	0.81	x		x	x	x
10	0.80	x		x	x	
11	0.82		x	x	x	x
12	0.82		x	x	x	

The best result in order to predict Modulus of Rupture (f_m) is obtained by model 12 (Table 3).

5.2 Reference method to determine Modulus of Elasticity

In both laboratories the Modulus of Elasticity was determined in three different ways:

- vibration measurements ($E_{m \text{ dyn}}$)
- bending method: measurement reference points in middle section and on both ends of the specimens ($E_{m \text{ stat total}}$)
- bending method: measurement reference points according to EN 408 ($E_{m \text{ stat local}}$)

Table 4. Results of the Modulus of Elasticity measurements.

	Douglas					Larch					
	N	Min	Max	Mean	Std. Dev.	N	Min	Max	Mean	Std. Dev.	
$E_{m \text{ dyn}}$	145	6.8	15.6	10.9	1.6	137	7.9	21.2	13.4	1.9	[GPa]
$E_{m \text{ stat total}}$	145	5.5	12.1	8.9	1.4	137	7.3	17.4	12.6	1.9	[GPa]
$E_{m \text{ stat local}}$	138	4.2	21.6	9.6	3.1	137	7.3	20.5	13.3	2.4	[GPa]

The results are presented in Table 4. The result for the complete sample are in good accordance with theory; in both laboratories the mean value of $E_{m \text{ stat local}}$ is higher than $E_{m \text{ stat total}}$ and $E_{m \text{ dyn}}$ compares best to $E_{m \text{ stat local}}$. Both effects can be explained by the influence of the shear deformation on the results of $E_{m \text{ stat total}}$. It is notable that the standard deviation from $E_{m \text{ stat local}}$ of the Douglas sample is clearly higher than from the Larch. When the measurements are evaluated from the perspective of the quality of the testing methods as a reference method, the variation between $E_{m \text{ stat local}}$, $E_{m \text{ stat total}}$ and $E_{m \text{ dyn}}$ for each individual specimen should be observed. The scatter diagrams below together with the regression coefficients show this variation clearly.

Table 5. Table Correlation coefficients between Moduli of Elasticity.

		Douglas	Larch
$E_{m \text{ stat local}}$	$E_{m \text{ dyn}}$	0.59	0.82
$E_{m \text{ stat local}}$	$E_{m \text{ stat total}}$	0.87	0.85
$E_{m \text{ stat local}}$	$E_{m \text{ stat local}}$	0.74	0.91

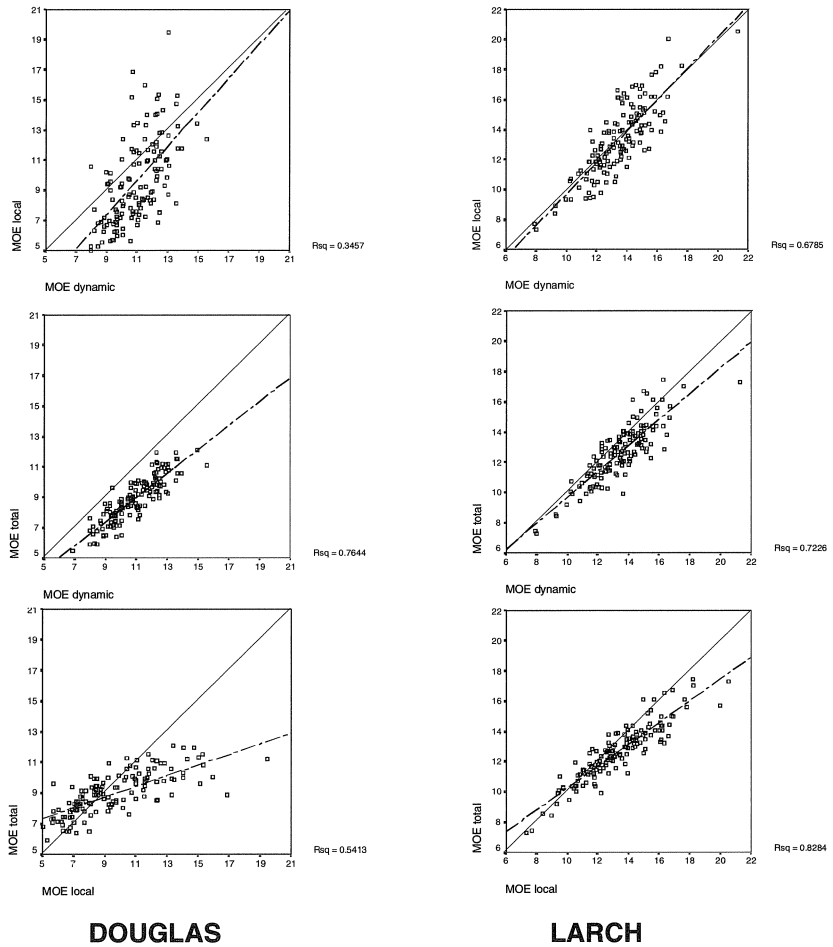


Fig. 12. Scatter diagrams of Moduli Elasticity.

From this table it is clear that with respect to the reproducibility the results of the two static bending arrangements show significant differences. Differences between the correlation between local, total and dynamic values can be explained to a certain extent by examining the error sources of the three measurements:

- $E_{m\ stat\ local}$ $E_{m\ stat\ total}$ (correlation coefficient: r_{lt})
- Apart from the effects of shear deformation (shear deformation results in lower values for $E_{m\ stat\ total}$, it does not effect r_{lt}), differences between local and global values are caused by variations of the characteristics (density, knots) along a specimen. $E_{m\ stat\ local}$ is based on the material characteristics of only the central 6D part of the pole, while $E_{m\ stat\ total}$ is based on the average properties of the full specimen. The variation in the properties of the central part with respect to the average properties is reflected in the correlation coefficient.

- The measurement of the deformations in the bending test arrangements is error-prone. Especially errors in the measurements of the deformations used to calculate $E_{m\ stat\ local}$ have strong impact on the accuracy this property can be determined with.
- $E_{m\ stat\ total}$ $E_{m\ dyn}$ (correlation coefficient: r_{td})
 - Both local and dynamic values are based on the full specimen's average properties. However, in the calculation of $E_{m\ dyn}$ the measured density of a pole is used, while in the calculation of $E_{m\ stat\ total}$ the pole geometry is used. So here, the cause of variation is the accuracy the density and geometry were determined with.
- $E_{m\ stat\ local}$ $E_{m\ dyn}$ (correlation coefficient: r_{ld})
 - $E_{m\ stat\ local}$ is based on the material characteristics of only the central 6D part of the pole, while $E_{m\ dyn}$ is based on the average properties of the full specimen. Differences between local and dynamic values are caused by variations of the characteristics (density, knots) along a specimen.
 - More variation is caused by errors in the determination of the density and geometry.

From the above it can be concluded that the mutual differences between the three correlation coefficients are expected to be as follows: $r_{lt} \cong r_{td} > r_{ld}$:

For Larch the correlation coefficients between $E_{m\ stat\ local}$, $E_{m\ stat\ total}$ and $E_{m\ dyn}$ yield explicable values: $0.91 \cong 0.85 > 0.82$.

The result for Douglas deviates from that what is expected. $0.74 < 0.87 > 0.59$. Both r_{lt} and r_{ld} are lower than expected.

As for both test arrangements the relation between $E_{m\ stat\ total}$ and $E_{m\ dyn}$ yields a reasonable value for the correlation coefficient, this leads to the conclusion that either in the test arrangement the Douglas material was tested, $E_{m\ stat\ local}$ was determined with lower accuracy or the Douglas test material was more sensible to local variations of the specimen properties.

and show the distribution of the RD_{II} values (discussed in) for both test arrangement. Although the average values for RD_{II} (5%) can be compared; the standard deviations (20%, 7%) show big differences.

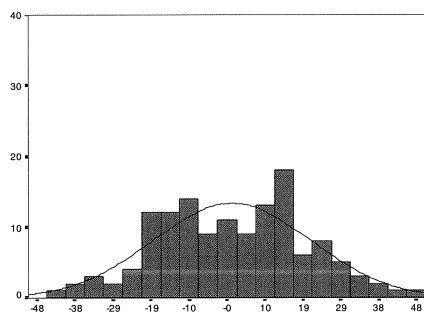


Fig. 13. Douglas RD_{II} [%]

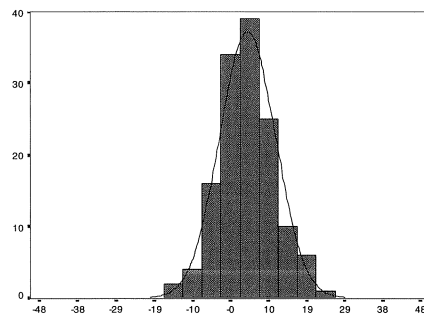


Fig. 14. Larch RD_{II} [%]

6 Conclusions

6.1 Grading system for roundwood

One of the key strength properties concerning strength classes [1] is the bending strength expressed by Modulus of Rupture. From the results obtained, the following conclusions can be drawn:

- The correlation coefficients of the regression models for roundwood correspond very well with models used for sawn timber in the wood industry [2].
- Visual features such as knots and growth rings are not able to predict Modulus of Rupture in a wide range of strength classes as defined in EN 338. The correlation coefficient for these characteristics is low. In order to optimise the yield throughout all strength classes a Modulus of Elasticity value should be brought into the model. The correlation coefficient (r) then increases from 0.70 to 0.82.
- Although the highest correlation can be achieved by model 12 (Table 3), from a practical point of view it would be recommended to use model 10. In this case the model parameters can be determined with less effort and higher reliability.
- In the situation that roundwood is used in constructions as an engineering material, it could be economically interesting to develop a grading machine for it. Due to the roundwood specific problems that raise with bending arrangements (see paragraph 5.2), it is proposed to implement the vibration measurement apparatus to determine the Modulus of Elasticity in such a grading machine.
- It is quite conceivable that for roundwood the existing strength classes and the procedures to calculate the characteristic values for sawn timber are suitable. According to the EN 384 (sawn timber) some correction factors have to be applied to calculate the characteristic values (size effect, influence of moisture content, etc.). For roundwood these correction factors have to be revised and adjusted.

Further it is necessary to investigate whether the strength values mentioned in the strength classes for sawn wood, derived from density, Modulus of Rupture and Modulus of Elasticity correspond with such for roundwood.

If the reference test arrangement for the determination of the physical properties of roundwood would be changed (e.g. $E_{m\ stat\ local}$ replaced by $E_{m\ dyn}$), the EN 384 procedure for the determination the characteristic values has to be adjusted accordingly.

6.2 Methods to determine Modulus of Elasticity as reference

- The results for Larch show that it is possible to carry out the accurate measurements using both local and total bending test arrangements. However, due to the high risk of introducing measurement faults (see paragraphs 4.3 and 5.2) when using the test arrangement described in EN 408, it is suggested to use the modified EN 408 (see paragraph) to determine $E_{m\ stat\ total}$ as a reference.
- A strong correlation between $E_{m\ static}$ and $E_{m\ dyn}$ is obtained ($r = 0.85$). Since the bending test arrangements, as described in EN 408 and their derivatives, includes uncertainties in measurement procedure and require huge effort to obtain reliable measurements, the vibration method provides a reliable alternative as reference.

Symbols

D	Pole diameter
E_m	Modulus of Elasticity
$E_{m \text{ dyn}}$	Modulus of Elasticity dynamic
$E_{m \text{ stat total}}$	Modulus of Elasticity according EN 408 modified
$E_{m \text{ stat local}}$	Modulus of Elasticity according EN 408
f_m	Modulus of Rupture
F	Force
MC	Moisture content
N	Number of growth rings
ρ_0	Specific gravity at 0% MC
R	Width of growth rings
RD_{it}	Characteristic value for test arrangement
RWC	Characteristic ringwidth value

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