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MULTIDIMENSIONAL STRENGTH PROPERTIES IN CLEAR WOOD SAMPLES OF CULTIVATED NORWAY SPRUCE

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Abstract:

Variation and co-variation are described for 15 strength parameters and density measured in mature plantation trees selected from Atlantic Norway. Results were generally comparable with standard listed values. Correlation between strength parameters was usually modest, but always positive. 53% of the overall strength variation could be extracted in the first principal component, closely related to density. All properties were more strongly correlated to density than to ring width. In addition to density, a substantial part, 5 to 30%, of strength variation could be attributed to tree effects. It was concluded that strength is multi-dimensional and suggested that there is potential for genetic selection to improve strength properties.

Key words*: density; strength correspondence; strength variation; genetic selection.*

INTRODUCTION

Strength is a general term used to describe the suitability of wood to be used in various applications, particularly in construction. For wood, strength can be considered both a contrast and a supplement to appearance and durability. Appropriate strength parameters are used to describe stiffness, rupture, splitting, efficiency of fasteners *etc*. Strength properties are regularly described in general wood technology textbooks (*e.g.* Tsoumis 1991, Niemz 1993, Shmulsky and Jones 2011), and further detailed in the reference book given by Bodig and Jayne (1993). Typical strength parameters for domestic use can be found in various handbooks, *e.g.* Treteknisk Håndbok (2009) for Norway and Wood Handbook (2011) for the USA.

Several strength parameters like rupture and cleavage can only be observed in destructive tests, which are obviously prohibitive for the subsequent utilisation of the wood specimen in question. Such parameters might either be estimated by correlation to other non-destructive observations or given in statistical terms calculated from observations in a representative sample from the same population. Estimation of Modulus of rupture (MOR) based on Modulus of elasticity (MOE) observed on dry boards, either alone or in combination with other predictors, is a well-established industrial practice (e.g. Hoffmeyer 1995, Bailleres *et al.* 2009). However, observations also made on green boards (Bailleres *et al.* 2009) or even on standing trees (Wessels *et al.* 2011) find some application. The advantage of grading kiln dried boards is high accuracy for the customers' benefit, while that of grading prior to kilning and break-down is to avoid the cost of processing timber that don't comply with customers' specifications.

Variability in properties is inherent in any natural material, and so also in wood. Due to the omission of knots, resin pockets, compression wood *etc.,* clear wood is considered more homogeneous than commercial boards (Wood Handbook 2011). Further, wood is anisotropic with distinctly different properties in the longitudinal, tangential and radial directions, which must be taken into account for several of the properties.

OBJECTIVE

The aim of the work reported in this paper has been to investigate the nature and variation of and interaction between a dozen various strength parameters. Strength and density variation within and between stems has been described. Correspondence in observed strength for sister samples were analysed and reported.

MATERIALS AND METHODS

Wood samples

Observations were made on specimens of clear, defect-free and mature wood of Norway spruce (*Picea abies* (L.) Karst.) prepared so that the faces corresponded to the wood structure. Ten clear, straight-grained samples of prescribed dimensions to be used for each of the various tests were extracted from each of 21 spruce stems. Each stem was divided in ten equally long sections, and specimens extracted from the lower five in this way: 3 from each of sections 1 (nearest to the base) and 2, 2 samples from section 3, and 1 from each of sections 4 and 5. Thus, a total of 210 specimens were sampled for each trait. Each specimen was labelled tree number - section number, and given an additional sequential number with no physical significance. Specimens from the same tree and section were considered "twin samples", *i.e.* assumed to have similar properties. Samples were left to dry in a ventilated shelter. Before testing, the specimens were acclimatised to ca. 12% moisture content (MC) and size adjusted by planing to prescribed dimensions.

Table 1

Descriptive statistics for the 21 sampled trees

Feature	unit	min value	average	max value
Age since planting	years	43	63	113
Tree height	m	17.9	24.0	28.3
Diameter BH w/bark	cm	20.8	28.4	37.5
Site index H_{40}	m	15.0	23.0	27.9

No native Norway spruce is found in the western, Atlantic region of Norway, west of the mountain range separating this landscape from the vigorously forested central and eastern regions. The only exception is a minor existence at Voss. This western region is fertile and well suited for spruce forestry, and consequently, during the last century an afforestation program has been carried out. Various spruce provenances have been used, some of national origin, others from central Europe. For this investigation, one tree was chosen from each of 21 sites in Sogn og Fjordane and Hordaland counties. The trees were of various characteristics (Tab. 1) and provenance: 4 of domestic, 10 of various continental European and 7 of unknown origin. The chosen trees should appear mature, sound and representing the typical wood quality for the stand. Each trunk was divided into 10 equally long sections, which were labelled, transported to the laboratory and stored in a moist and refrigerated climate until further processing, as previously described.

Strength testing

The test samples were made up of clear, defect-free wood aligned to the wood structure: radial, tangential and longitudinal. Observations were made according to the Scandinavian norm SKANORM (1992). Brief comments on correspondence to BJ (Bodig and Jayne 1993) and WH (Wood Handbook 2011) are given for reference. The following properties related to wood strength were observed:

- Static MOR, Modulus of rupture: Testing was performed according to general accepted procedure and calculated according to BJ Eq. 9.19. Same specimens as MOE deflected at one central point.
- Static MOE, Modulus of elasticity: Observed deflection over 300 mm length at two symmetric points 100mm apart; specimen dimension 20 * 20 * 340mm. Testing was performed according to general accepted procedure and calculated according to BJ Eq. 9.20.
- Shear parallel to grain: Testing was performed according to general accepted procedure and calculated according to BJ Eq. 9.17. Specimen gross size 50 * 50 * 63mm cut to L-shape; separate specimens for the tangential and the radial directions.
- Compression: Tested in the general manner (see BJ), separate specimens for orthogonal (⊥, O) to grain and parallel (**II**, P) to grain; specimen dimension 20 * 20 * 60mm.
- Toughness: Tested by pendulum impact on radial face on specimens 20 * 20 * 300mm. Toughness has been observed in various ways; according to BJ toughness is a "secondary test" and observed "toughness data cannot be used for other than comparative purposes".
- Hardness: Observed the force required to press the full radius of a sphere with radius 5.64mm into the same wood sample in each direction: radial, tangential and longitudinal; specimen dimension 50 * 50 * 50mm. According to BJ hardness is a "secondary test" "useful for comparative purposes".
- Cleavage: Observed the force needed for cleaving in the tangential direction of specimens 20 * 20 * 45mm, with a wedge cut and a radius = 2mm hole drilled at the wedge's bottom, leaving 20mm of unharmed wood in the lengthwise direction. WH describes several crack propagation systems, but none of which accepted as standard; according to BJ "cleavage ... tests now receive limited use". Observations according to SKANORM are reported.
- Withdrawal load (WL): Test of nail and screw fastening to the wood, average of two observations in each of the radial and tangential directions, respectively; expressed in load per unit length of connector penetration into the 50 * 50 * 150mm wood samples; separate samples for nail and screw WL. For reference, observed values were compared to WH Eq. 8-1a (nails) and Eq. 8-10a (screws).
- Density: Actual density at 12% moisture content was observed on each specimen for each trait. Density is a significant property in its own importance and influential for most strength parameters.

After each test, moisture content (MC) was verified by the dry weight method and observed values adjusted according to (SKANORM 1992). Statistica 64 v.10 software (Statsoft 2012) was applied for all statistical calculations.

RESULTS AND DISCUSSION

Observed strength and variation in strength properties

Average and variation for all observed properties incl. density are listed in Tab. 2. Density corresponds to the density values reported for Norway spruce from traditionally forested areas in the south-eastern part of Norway (Bramming 2006); nevertheless, mean MOR was 4% and MOE 12% lower. Most strength parameters corresponded quite well to matching North American spruce wood as tabulated in Wood Handbook (2011).

The observed coefficient of variation (CV) for most standardized strength parameters were in the range 15 to 25%. Toughness and nail withdrawal values demonstrated somewhat higher variation, and density and screw withdrawal load, lower variation. Generally, the calculated values for CV corresponded well to standard listed figures (Wood Handbook 2011).

Most properties appeared normally or close to normally distributed; however, due to the limited numbers of trees in the sample, no distinct conclusion should be drawn in this respect. A few properties, *e.g.* toughness and nail withdrawal load, were skewed with a tail towards high observations; these were the properties with the highest values for CV.

Table 2

Mean observed strength, standard deviation s and coefficient of variation CV, as compared to values listed in Wood Handbook (2011) WH; all values at 12% MC

Strength trait	**unit**	**Mean**	**s**	**CV**	**WH mean**[1]	**WH CV**[2]
MOR	MPa	71.7	12.1	0.168	70	0.16
MOE	MPa	11 890	2541	0.214	10 800	0.22
Shear Tan	MPa	6.41	1.08	0.168	7.9	0.14
Shear Rad	MPa	6.78	0.88	0.130		
Compression O	MPa	2.17	0.55	0.254	4.0	0.28
Compression P	MPa	35.8	5.23	0.146	38.7	0.18
Toughness Rad	J/mm^2	2.90	0.93	0.321	4.5[3]	0.34
Hardness Tan	N	1 621	293	0.181	2 300	0.20
Hardness Rad	N	1 855	303	0.163		
Hardness Len	N	2 491	370	0.148	-	-
Cleavage Tan	N/mm	10.53	1.55	0.147	-	-
Nail WL Tan	N/mm	14.26	3.35	0.235	23	-
Nail WL Rad	N/mm	11.78	3.73	0.317		
Screw WL Tan	N/mm	96.3	12.1	0.125	69	-
Screw WL Rad	N/mm	91.2	14.0	0.153		
Density MC = 12%	kg/m^3	396	41	0.103	400	0.10

[1] WH for Sitka spruce Table 5-3a, Eq. 8-1a (nail) and Eq. 8-10a (screw) withdrawal load

[2] WH Table 5-6 (general values for clear wood)

[3] WH for Engelmann spruce Table 5-9

Source of variation

Most strength properties were moderately and positively correlated to density (Tab. 3); only cleavage and tangential shear demonstrated r less than 0.6. Most properties demonstrated negative correlation to mean ring width; this correlation was always considerably weaker than to density. The correlation between density and strength properties was considerably higher than figures reported for commercial boards. As an example, Hoffmeyer (1995) reported correlation coefficient r between density and MOR in the range 0.40 - 0.63 for commercial boards, as compared to 0.90 for clear wood samples in this investigation. This is quite unsurprising: Commercial boards are less uniform than defect-free samples.

Variances were analyzed, applying general linear models (GLM). Predictors were density observed directly on the tested specimen (continuous variable), and tree and section number (categorical variables). Predictors were entered in a fixed sequence: first density, next tree number and finally section number. After each step, the fraction of variance accounted for by the model (R^2) was recorded, and the increase in R^2 was attributed to the last entered predictor. Results are listed in the right part of Tab. 3 and illustrated in Fig. 1.

Next to density, between-tree variation is most apparent. Bearing in mind that this is a 'tree effect' beyond what can be explained by density, this points to a genetic influence. Consequently, timber strength might be improved by selection of the strongest trees for any given level of density. The additional effect of section number, *i.e.* height in stem, is low and can generally be disregarded. Residuals represent variation between samples assumed to have similar properties. Residuals are of substantial magnitude, typically 20-30% of the variation. For cleavage and tangential shear the residuals are exceptionally high, over 50%; these two properties are atypical among the investigated strength properties.

As described, density was observed on each single specimen. The density variation between "twin specimens" was analyzed, and the standard error was calculated to 17 kg/m^3. Wood density is known to vary in an intricate way with distance from the pith (see *e.g.* Niemz 1993). The samples used in this investigation were extracted in mature wood, but otherwise at random distance from pith. This is probably the main reason for the observed standard error in density, and a contribution to the residuals in strength properties.

Table 3

Source of variation in strength properties:
Left: Correlation r to specimen density and mean ring width, respectively
Right: Fraction of trait variation associated with density, tree and section, respectively, and residuals

Strength trait	**Correlation r to**		**Source of variation (Degr. freed. in brackets)**			
	Density	**Ring width**	**Density (1)**	**Tree (20)**	**Section (4)**	**Residual (184)**
MOR	0.90	-0.60	81.5 %	5.0 %	0.2 %	13.3 %
MOE	0.74	-0.46	54.3 %	8.4 %	2.0 %	35.3 %
Shear Tan	0.28	0.07	7.7 %	27.1 %	6.8 %	58.4 %
Shear Rad	0.62	-0.41	38.5 %	31.3 %	2.5 %	27.7 %
Compression O	0.75	-0.53	56.5 %	20.7 %	1.1 %	21.7 %
Compression P	0.93	-0.69	87.2 %	4.7 %	1.4 %	6.7 %
Toughness Rad	0.65	-0.49	42.4 %	13.6 %	2.6 %	41.4 %
Hardness Tan	0.87	-0.49	73.9 %	8.6 %	0.4 %	17.1 %
Hardness Rad	0.86	-0.36	75.9 %	7.3 %	1.2 %	15.6 %
Hardness Len	0.74	-0.28	54.3 %	24.7 %	1.9 %	19.1 %
Cleavage Tan	0.20	0.00	3.8 %	20.8 %	8.7 %	66.7 %
Nail WL Tan	0.73	-0.45	54.3 %	16.7 %	1.5 %	27.5 %
Nail WL Rad	0.74	-0.57	53.6 %	17.2 %	1.7 %	27.5 %
Screw WL Tan	0.76	-0.20	53.7 %	14.1 %	2.6 %	29.6 %
Screw WL Rad	0.73	-0.24	57.5 %	22.1 %	3.8 %	16.6 %
Density MC = 12%	-	-0.65	-	89.8 %	0.1 %	10.1 %

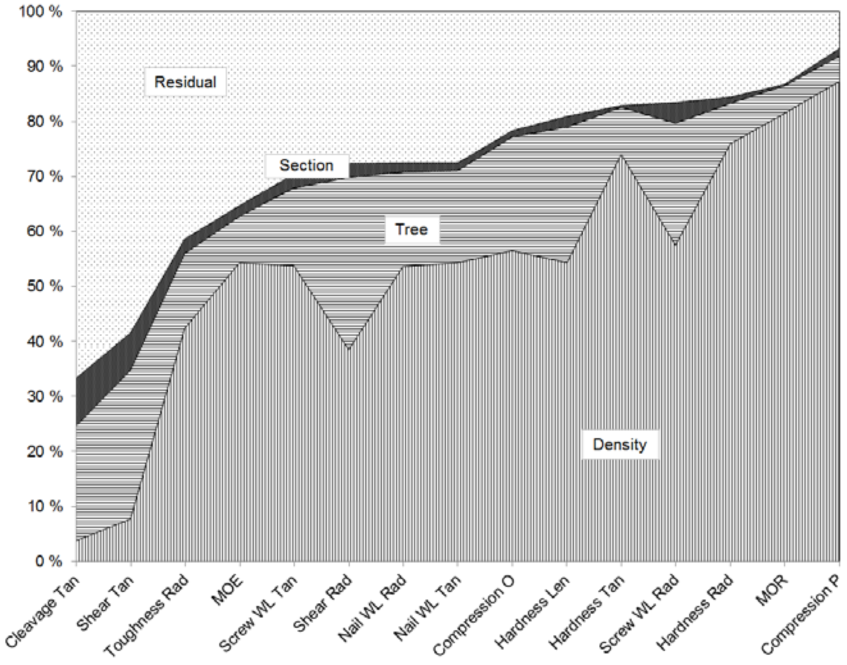

Fig. 1
Fraction of variation associated with density, tree, section and residuals.

Correlation between various trait parameters

Calculated correlation coefficients are listed in Tab. 4. Properties were generally positively correlated, and at the same level of agreement as that between density and each property. The major exception was cleavage, which is virtually uncorrelated to the other properties, as it is to density. Even between similar tests made on the same specimen only modest, albeit always positive, correlation appeared: Screw withdrawal load 0.80, nail withdrawal load 0.73 and hardness in three directions 0.74 to 0.81.

This correlation could all be connected to density, and a principal component analysis performed on the 15 strength properties revealed that 53% of the variation could be extracted in the first factor (Fig. 2). Also, all properties appear in the same direction, negative values for factor 1, "the density factor". Factor 2 joins the two properties cleavage and tangential shear in a common group, separated from the others. Factor 2 accounts for 9% of the overall variation; all other factors represent 6% or less.

Table 4

Correlation coefficient r between various strength properties

Trait →	**No.**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**
MOR	1														
MOE	2	0.80													
Shear T	3	0.23	0.17												
Shear R	4	0.58	0.45	0.12											
Compr. O	5	0.53	0.36	0.20	0.35										
Compr. P	6	0.69	0.58	0.20	0.47	0.49									
Tough R	7	0.48	0.43	0.08	0.25	0.40	0.49								
Hard T	8	0.65	0.53	0.34	0.58	0.52	0.64	0.45							
Hard R	9	0.65	0.49	0.29	0.52	0.65	0.64	0.51	0.78						
Hard L	10	0.53	0.42	0.37	0.53	0.55	0.57	0.40	0.74	0.81					
Cleav T	11	0.09	0.00	0.28	0.05	0.21	0.04	0.10	0.16	0.19	0.20				
Nail T	12	0.60	0.47	0.15	0.52	0.52	0.52	0.45	0.58	0.69	0.63	0.06			
Nail R	13	0.58	0.40	0.28	0.50	0.44	0.50	0.37	0.66	0.67	0.65	0.20	0.73		
Screw T	14	0.62	0.49	0.36	0.50	0.52	0.59	0.40	0.68	0.71	0.70	0.17	0.61	0.55	
Screw R	15	0.63	0.49	0.45	0.51	0.44	0.61	0.36	0.70	0.70	0.74	0.22	0.59	0.70	0.80

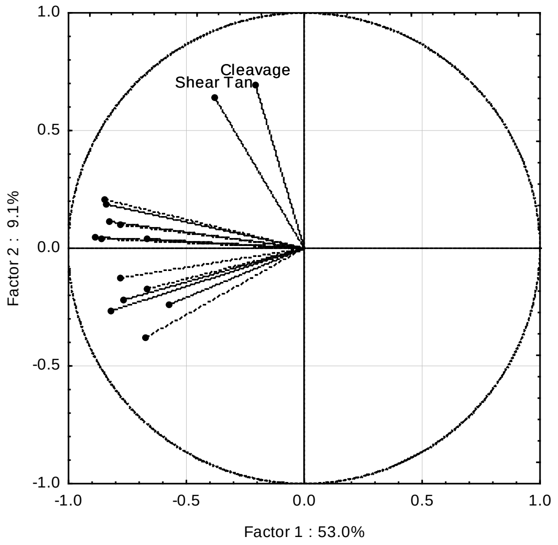

Fig. 2
Principal components, two first factors for the 15 strength properties.

CONCLUSIONS

- Approximately 50% of the overall variation in fifteen strength parameters is attributed to density variation.
- A substantial tree effect on strength, in addition to the density effect, indicates a potential for improving strength properties by genetic selection.
- Beyond the density and tree effect, strength properties are mutually independent, leaving strength as multidimensional properties.

- Cleavage and tangential shear correlate weakly to density and to other strength properties.
- Correlation for strength properties is always considerably weaker for ring width than for density.

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