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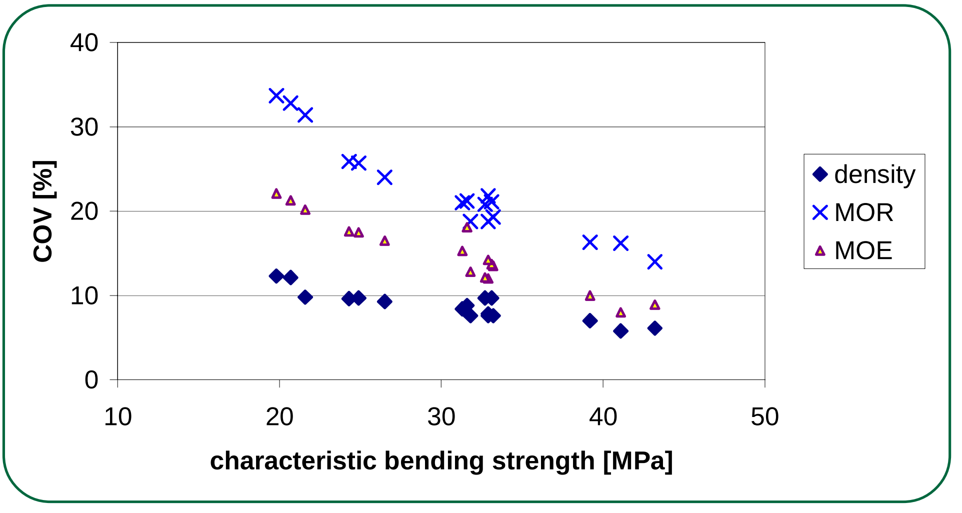

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VTT PUBLICATIONS 668

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ISBN 978-951-38-7067-6 (soft back ed.)
ISSN 1235-0621 (soft back ed.)

ISBN 978-951-38-7068-3 (URL: http://www.vtt.fi/publications/index.jsp)
ISSN 1455-0849 (URL: http://www.vtt.fi/publications/index.jsp)

JULKAISIJA – UTGIVARE – PUBLISHER

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Technical editing Leena Ukskoski

Edita Prima Oy, Helsinki 2008

Ranta-Maunus, Alpo. Strength of Finnish grown timber [Suomalaisen puun lujuustutkimusten yhteenveto]. Espoo 2007. VTT Publications 668. 60 p. + app. 3 p.

Keywords timber, wood, spruce, pine, strength, bending, tension, compression, shear, creep, duration of load

Abstract

Strength and stiffness of timber have been studied in different projects during 1986–2007. This is a summary report of results which are considered relevant for European and international standardisation. It includes both new unpublished and already published information. The growth area of timber considered in this publication is primarily limited to Finland and parts of North Western Russia.

This experimental research concerns bending, tension, compression and shear strength and stiffness of sawn timber. It includes also tension perpendicular to grain of glulam and compression perpendicular to grain of sawn timber. Also, bending and compression strength of round timber is reported. In addition, long term creep results of glulam and other structural wood products are included in this publication.

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Tiivistelmä

Julkaisu on yhteenveto puun lujuutta koskevista tutkimuksista VTT:ssa 1986–2007. Osa koetuloksista on ennen julkaisemattomia, osa on aikaisemmin julkaistuja. Julkaisu keskittyy sellaisiin tuloksiin, joilla on ilmeistä käyttöä puurakenteiden standardeja ja normeja kehitettäessä.

Tutkimus rajoittuu Suomessa ja lähialueilla kasvaneeseen kuuseen ja mäntyyn. Tuloksia verrataan myös julkaistuihin eurooppalaisiin tutkimustuloksiin. Julkaisu sisältää sahatavaran taivutus-, veto-, puristus ja leikkauslujuustuloksia ja liimapuun lujuustuloksia syysuuntaa vastaan kohtisuoran vetorasituksen alaisena sekä liimapuun virumistuloksia 16 vuotta kestäneen kuormituksen alaisena. Julkaisu sisältää myös pyöreän puun taivutus- ja puristuskoetuloksia.

Preface

This report is a summary of experimental research results on strength of timber in different projects. The main reason for writing this report is to make results easily available for European and international standard writers.

This report includes both new and already published data on strength and stiffness of timber grown in Finland or neighbouring area. New data which has not been previously published is obtained in Combigrade-projects during 2006 by VTT and Helsinki University of Technology TKK. These projects were funded by the Finnish Funding Agency for Technology and Innovation Tekes, Wood Focus Ltd, Finnish glulam industry, Finnforest, Stora Enso, UPM and VTT. Several collaboration partners were working in Combigrade project performing parts of strength grading. The main aspect of Combigrade was strength grading which has been reported elsewhere.

Contents

1. Introduction

The background of this research is that there are still issues related to strength of timber which need new information to be satisfactorily resolved. As an example, tension strength of sawn timber is assumed to be 60% of bending strength in European standardisation. A motivation for this research was to demonstrate that the tension strength is higher as indicated by earlier studies. In fact, tension strength of sawn timber used in structures is not a dimensioning property, because the tensile member has to be jointed to other members and connections are usually critical in structural design. Tension strength is, however, of practical importance when using strength graded sawn timber as glulam lamellas. This report includes new test results. All experimental results reported here, if not otherwise indicated, are based on testing in accordance with EN 408 as further specified in EN 384 for determination of characteristic values.

In Europe the main commercial species used in construction is European spruce. However, exporters have problems in Far East where spruce is not traditionally known. This research is expected to show that strength of spruce is on equivalent level with pine, and quite high. Even the ungraded population of Nordic spruce timber meets the requirement of characteristic strength of grade C24.

Shear strength of timber is under discussion in Europe. There are suggestions to lower shear strength because of roof failures taken place in Germany. This is not considered to be the right measure, because failures are resulted by moisture induced stresses which are caused by annual climate variations during the use of building. It is believed that the right approach is to consider moisture effects as load on structure, not as strength reduction, because "strength reduction" approach would lead to zero strength with regard to shear and tension perpendicular to grain, when moisture gradient is strong enough to cause cracking of timber. Shear strength is obviously not a dimensioning property of timber beams. From experiments we know that shear failure of a beam is seldom even if the experiment is planned to produce shear failure mode. The exception is loading of severely pre-cracked beam, or possibly loading of glulam beam which has high tension stresses perpendicular to grain due to moisture variation. In these cases timber beam can fail in shear mode. The other occasion where shear strength is needed is dimensioning of connections. This report includes test results of shear strength of wood material and long term tests of glulam under tension perpendicular to grain stresses caused by combination of mechanical and moisture load.

In structural design the creep deflection under long term loading is calculated. This report has new results on creep of glued laminated timber during 16 years under low load levels comparable to dead load of roofs in Nordic countries.

Timber structures have been traditionally designed to carry mainly compression loads. Design against compression seems less problematic, at least in dimensioning of columns strength is not often critical, when there are other factors which determine the dimensions. However, compression test results are included in the report.

2. Sawn timber

2.1 Bending strength and stiffness

2.1.1 Characteristics of unsorted timber

Results of two projects are reported here. Both consist of testing of spruce (*Picea abies*) and pine (*Pinus sylvestris*). The former research has been reported in greater detail by Ranta-Maunus et al. [2001]. The aim of sampling was to be representative for spruce timber grown in Finland. The later is Combigrade project and its materials and methods are described in Appendix A and by Hanhijärvi and Ranta-Maunus [2008]. Combigrade project sampling was made for strength grading purposes, and it includes also logs of lower quality than normally used for sawn timber. Diameter of logs was smaller than the average used for sawn timber.

In the former project spruce was sampled from six different locations in Finland as well as from one location in Sweden. Pine was sampled from one location in Finland as well as from one location in Sweden. Both spruce and pine were randomly sampled from ungraded lots of sawn timber. Sample size, dimensions, and mean values of bending strength (edgewise), density and modulus of elasticity (local) are given in Table 1, where years 1986–1997 refer to the former research. VTT has tested Finnish grown timber and Trätek Swedish grown timber. Variation of density, bending strength and modulus of elasticity within major test series is summarised in Table 2. Coefficient of variation (COV) of density of unsorted samples is about 10%, COV of bending strength from 20 to 40% and COV of MOE from 15 to 24%. In general, the variation of properties of spruce is smaller than that of pine.

Table 1. Mean values of characteristics in different test series: width, b, depth, h, moisture content, ω, density, ρ, bending strength, f, and modulus of elasticity, E where E is local MOE and ρ is measured from small specimens at test conditions.

Species	Series	Number	b mm	h mm	ω %	ρ kg/m³	f N/mm²	E N/mm²	Data source
Spruce	S-1	589	42	146	14.7	448	45.2	13 000	VTT 1995
Spruce	S-2	150	72	221	14.6	415	38.1	10 800	VTT 1996
Spruce	S-3	149	35	97	14.6	457	46.9	12 800	VTT 1996
Spruce	S-4	172	45	172	12.2	435	42.8	11 900	VTT 1997
Spruce	S-5	167	35	120	11.4	456	44.3	12 200	VTT 1997
Spruce	S-97	122	45	95	11.5	497	39.6	-	TRÄTEK 1990
Spruce	S-98	80	45	145	11.0	479	42.0	-	TRÄTEK 1990
Spruce	S-99	79	45	190	10.3	462	34.0	-	TRÄTEK 1990
Spruce	K0	201	38	100	10.6	437	45.6	11 600	Combigrade
Spruce	K100	211	50	100	11.1	442	48.2	12 300	Combigrade
Spruce	K200	214	50	151	11.0	443	46.3	12 400	Combigrade
Spruce	K300	156	63	201	11.5	434	41.3	12 200	Combigrade
Spruce	K400	139	44	200	10.8	428	35.6	11 300	Combigrade
Pine	P-1	188	42	146	13.6	508	48.5	12 800	VTT 1995
Pine	P-97	100	45	95	15.0	471	37.9	10 400	TRÄTEK 1986
Pine	P-98	99	45	145	15.3	475	38.1	10 100	TRÄTEK 1986
Pine	P-99	100	45	190	15.1	477	38.8	10 000	TRÄTEK 1986
Pine	M0	205	39	100	11.0	458	41.1	10 900	Combigrade
Pine	M100	211	50	100	10.6	456	40.6	10 500	Combigrade
Pine	M200	194	50	151	10.5	461	39.5	11 100	Combigrade
Pine	M300	183	63	201	11.1	483	39.8	11 700	Combigrade
Pine	M400	141	44	200	10.5	496	36.8	11 600	Combigrade

Before analysis, all individual bending strength values were adjusted to a reference depth of 150 mm according to EN 384. Furthermore, all individual modulus of elasticity and density values were adjusted to a moisture content of 12% according to EN 384.

In series S-1, the depth of all the 589 specimens was about 146 mm which is close to the reference depth. Hence, the effect of size on bending strength did not affect the results. The mean moisture content of the specimens was 14.7% while the standard deviation was 1.5%. This resulted in a little lower bending strength values than for specimens of 12% moisture content. The bending strength, *f*, is plotted against the modulus of elasticity, *E*, in Figure 1. Using linear regression analysis the relationship is given by

$$f = -2.66 + 0.00392E \text{ and } R^2 = 0.65 \quad (1)$$

In Figure 1 and in Equation (1) the bending strength as well as the modulus of elasticity obtained from the tests were used without any depth or moisture content adjustments.

Based on Combigrade data, including different dimensions and adjusting bending strength to reference size 150 mm we obtain for spruce

$$f = -4.91 + 0.00401E \text{ and } R^2 = 0.63 \quad (2)$$

and for pine

$$f = -10{,}72 + 0.00448E \text{ and } R^2 = 0.68 \quad (3)$$

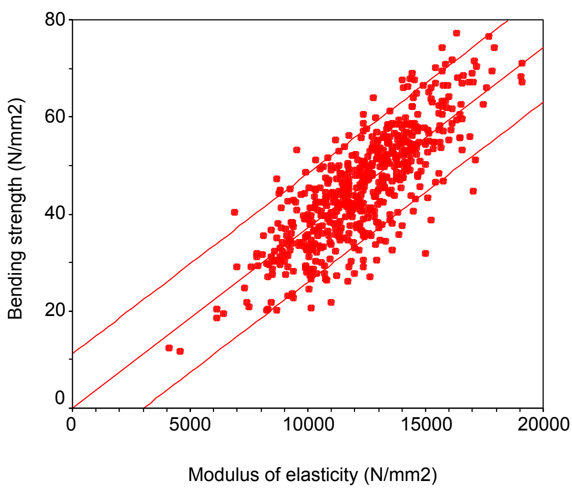


Figure 1. The relationship between bending strength and modulus of elasticity for spruce with a depth of 150 mm, series S-1. The linear regression line and the 90% confidence interval are included.

Table 2. Variation of density, ρ, bending strength, f, and local modulus of elasticity, E.

Series	Number	ρ		f		E	
		Mean kg/m^3	COV %	Mean N/mm^3	COV %	Mean N/mm^3	COV %
S-1 & S-98	589	448	9.0	45.2	25.2	13000	18.8
S-1 to S-99	1508	451	9.7	43.1	27.1	12400	19.8
K0	201	437	10.0	45.6	22.2	11600	18.5
K100	211	442	9.0	48.2	20.9	12300	15.5
K200	214	443	10.5	46.3	24.8	12400	17.3
K300	156	434	9.2	41.3	24.1	12200	15.9
K400	139	428	9.0	35.6	31.6	11300	19.8
K0 to K400	921	438	9.7	44.1	25.8	12000	17.6
M0	205	458	10.4	41.1	30.8	10900	20.7
M100	211	456	11.2	40.6	34.7	10500	23.4
M200	194	461	10.6	39.5	33.0	11100	20.7
M300	183	483	13.4	39.8	33.3	11700	21.1
M400	141	496	13.3	36.8	38.4	11600	22.6
M0 to M400	934	468	12.2	39.7	33.9	11100	22.1

2.1.2 Modelling of strength

2.1.2.1 Modelling by dynamic modulus of elasticity

Size adjusted bending strength obtained from Combigrade data was first modelled by using dynamic modulus of elasticity as the strength indicator. The size effect was also included in the analysis. The first model fitted to data was

$$f_{m,adj,model} = e^{a_0} * \left(\frac{h}{h_{ref}}\right)^{a_1} * \left(\frac{b}{b_{ref}}\right)^{a_2} * \left(\frac{E_{dyn}}{E_{dyn,ref}}\right)^{a_3} \tag{4}$$

where h_{ref} = 150 mm, b_{ref} = 50 mm, $E_{dyn,ref}$ = 12 500 MPa and E_{dyn} is based on measurement of natural frequency and density. Results obtained in regression analysis for model (4) are given in Table 3.

Also a simple linear model was fitted to spruce material (four dimensions excluding 63 x 200) E_{dyn} being the only variable which gave result

$$f_{m,adj} = 0,00395E_{dyn} - 6,373 \qquad R^2 = 0.59 \tag{5}$$

Table 3. Results obtained in regression analysis when using model (4).

Material	**a_0**	**a_1**	**a_2**	**a_3**	**R^2**
pine, all 5 dimensions	3.788515365	-0.01843	0.167005	1.440592493	0.70
pine, 4 dimensions	3.789478797	-0.01718	0.1738	1.439485862	0.71
spruce, 4 dimensions	3.752235734	-0.07663	0.263538	1.133972058	0.60

Also a prediction for the lower five percentile fractiles were modelled by the use of sliding 5 percentiles of 50 values. For spruce we obtained, based on the linear model

$$f_{m,k} = 0.00357E_{dyn} - 12.645 \tag{6}$$

and based on model (4):

$$f_{m,k} = af_{model} + b \tag{7}$$

where coefficients a and b are given in Table 5. Please observe that values given in CIB paper [Hanhijärvi et al. 2007] related to Equations (4) and (6) are those for pine instead of spruce claimed in the paper.

2.1.2.2 Modelling by KAR and density

In the second case, adjusted bending strength was modelled by using both knot area ratio KAR and density as strength indicating parameters as follows

$$f_{m,adj,model} = e^{a_0} * \left(\frac{h}{h_{ref}}\right)^{a_1} * \left(\frac{b}{b_{ref}}\right)^{a_2} * \left(\frac{KAR}{KAR_{ref}}\right)^{a_3} * \left(\frac{dens}{dens_{ref}}\right)^{a_4} \quad (8)$$

with values h_{ref} = 150 mm, b_{ref} = 50 mm, KAR_{ref} = 0,2, $dens_{ref}$ = 450 kg/m^3.

Results of regression analysis are given in Table 4. Also this model was used to predict 5 percentile of bending strength based on sliding 5 percentiles and fitting a linear model to the 5 percentiles. Coefficients obtained for Equation (7) are given in Table 5.

Table 4. Results of regression analysis for modelling bending strength as function of KAR and density as in Equation (8).

	a_0	a_1	a_2	a_3	a_4	R^2
pine, 5 dim	3.439723007	-0.24082	0.152993	-0.18717	1.794648	0.63
spruce, 4 dim	3.665306358	-0.21953	0.182431	-0.22605	1.102889	0.48

Table 5. Coefficients a and b for Equation (7) for estimation of 5 percentile values. Results obtained in regression analysis when using strength model (4) or (8).

Material	Model (4)		Model (8)	
	a	b	a	b
pine, all 5 dimensions	0.8638	- 4.5858	0,7751	-2,8594
pine, 4 dimensions	0.8668	- 4.9896		
spruce, 4 dimensions	0.874	- 5.1334	1,0229	-11,538

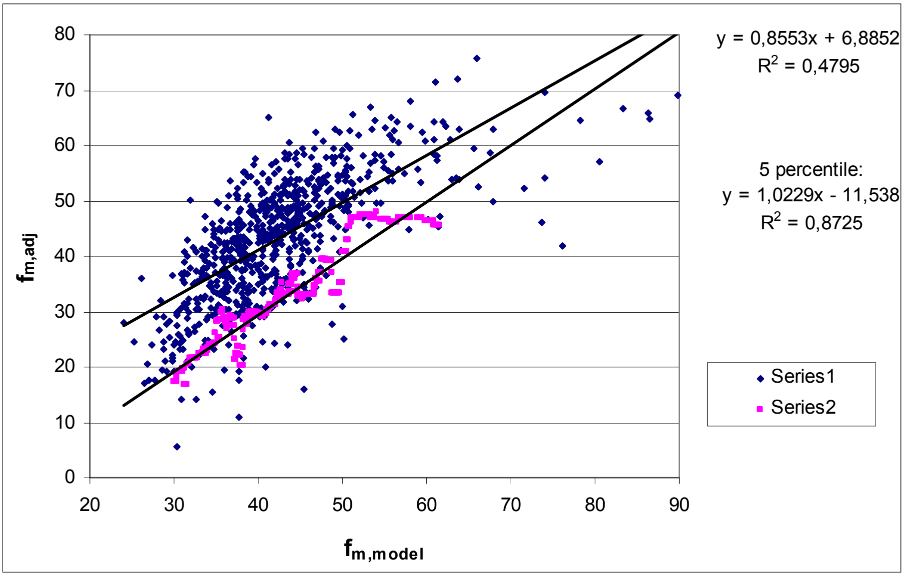


Figure 2. Observed bending strength of spruce vs. modelled (8) based on 4 dimensions. Sliding 5 percentiles (series 2) with a fitted trendline are also shown.

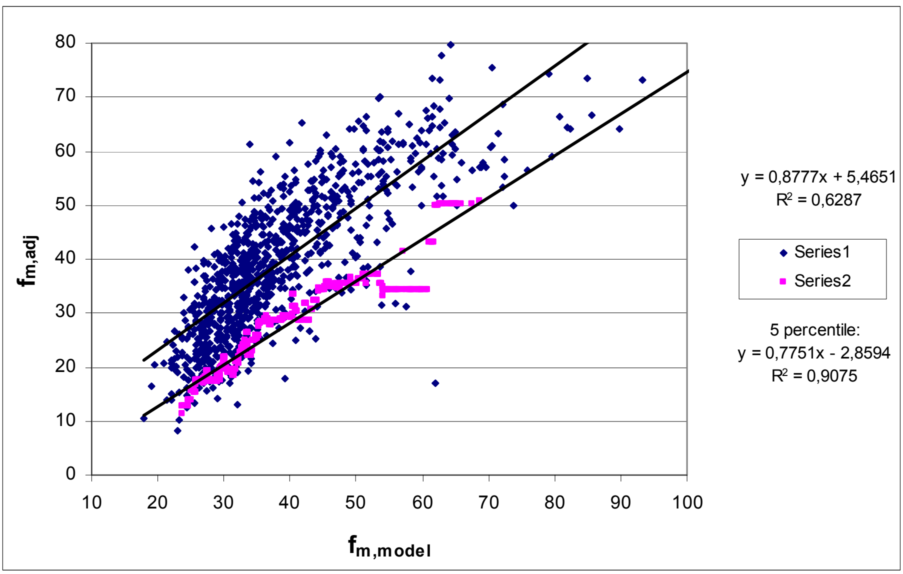


Figure 3. Observed bending strength of pine vs. modelled (8) based on 5 dimensions tested. Sliding 5 percentiles (series 2) with a fitted trendline are also shown.

In both cases, the regression analysis of spruce timber is based on strength data of four dimensions (excluding 63 x 200) and the regression analysis of pine timber is based on strength data of all five dimensions.

2.1.3 Results for graded timber

In series S-1 to S-99, the depths of specimens were between 95 and 221 mm. The tested bending strength values were adjusted to a reference depth of 150 mm and modulus of elasticity and density values were adjusted to a moisture content of 12% according to EN 384. The mean moisture content of the specimens was 13.3% while the standard deviation was 2.0%. Visual grading was made according to the Nordic grading rules given in INSTA 142 to a grade equivalent to C24. Grading was carried out in laboratory with no time limit. Machine grading was made by use of Raute bending type machine to one grade equivalent to C30, corresponding to settings used in mid 1990's.

Combigrade material was graded to artificial grades based on Equations (4) and (8). Grades are defined as $f_{model} > 20$ and $f_{model} > 40$. The lower grade includes practically all material, and the higher grade roughly the better half. The density, bending strength and modulus of elasticity of these data sets are summarised in Table 6.

Third kind of grading is made by using threshold values for E_{dyn}, KAR and density, in order to compare the effectiveness of a linear strength model to exclusion of worst specimens while aiming to similar kind of yields. The following grades are defined:

1: G1: E_{dyn} > 7000 MPa, and KAR < 0.4 and density at 12% MC > 400 for pine, and > 360 kg/m^3 for spruce.

2: G2: E_{dyn} > 10 000 MPa for pine and > 11 000 for spruce, and KAR < 0.25 and density at 12% MC > 440 for pine, and > 400 kg/m^3 for spruce.

3: G3: E_{dyn} > 13 000 MPa, and KAR < 0.25 and density at 12% MC > 440 for pine, and > 400 kg/m^3 for spruce.

4: G4: E_{dyn} > 14 000 MPa, and KAR < 0.25 for pine and <0.2 for spruce, and density at 12% MC > 440.

Requirements for the lower grades (f_{model} > 20 or G1 with threshold limits) are such that the number of rejects is small in Combigrade material. Yield to the lower grades amounts from 88 to 100%. For the better grades (f_{model} > 40 or G2 with threshold limits) yield amounts from 34 to 60% being in the same range as in case of test series "S-1 to S-99" where visual grading to C24 gave a yield of 52% and machine grading to C30 gave yield 65%. 5 percentile of strength in all these cases where yield is from 34 to 65% is above 30 MPa (from 31.6 to 33.2). For ungraded timber, as in case f_{model} > 20, 5 percentile of bending strength of Combigrade material is 20 MPa for pine and 24 MPa for spruce. The highest grade G4 had a yield 17% for spruce and 19% for pine, and resulted in 5 percentiles of bending strength above 40 MPa.

The relation of yield and characteristic bending strength is illustrated in Figure 5. Different grading methods have similar trends, but methods which include measurement of dynamic modulus of elasticity are more efficient. Figure also shows that spruce gives higher yield to strength grades than pine. At highest grades yields are equal. These yields are based on Combigrade material, other sampling might give different yields.

Figure 4 illustrates variability of density, stiffness and strength in different grades based on numbers given in Table 6. The clear trend is that coefficient of variation decreases when characteristic strength increases. COV of bending strength, modulus and elasticity and density of grade C40 is only half of the COV values for C22.

Table 6. Density, ρ, bending strength, f, and local modulus of elasticity, E, for some samples of graded timber.

Test series	Grade	N (yield %)	ρ Mean kg/m³	ρ COV %	f Mean N/mm²	f COV %	f 5 %-tile N/mm²	E Mean N/mm²	E COV %
S-1 to S-99	C24 visual lab	781 (52)	447	8.8	47.3	21.2	31.6	13 000	18.1
S-1 to S-99	C30 machine	986 (65)	465	8.4	47.8	21.0	31.3	13 400	15.3
K0 to K400	Edyn, f_{model}>20	909 (100)	438	9.7	44.1	25.7	24.9	12 000	17.5
K0 to K400	Edyn, f_{model}>40	562 (62)	458	7.6	49.5	18.8	32.9	13 200	12.0
K0 to K400	KAR + ρ, f_{model} >20	909 (100)	438	9.6	44.1	25.9	24.3	12 000	17.6
K0 to K400	KAR + ρ, f_{model} >40	531 (58)	459	7.6	49.5	19.3	33.2	13 100	13.5
M0 to M400	Edyn f_{model} >20	910 (100)	470	12.1	40.3	32.8	20.7	11 200	21.3
M0 to M400	Edyn f_{model} >40	362 (40)	518	9.7	51.5	20.8	32.7	13 500	12.1
M0 to M400	KAR + ρ, f_{model} >20	911 (100)	469	12.3	39.8	33.7	19.8	11 100	22.1
M0 to M400	KAR + ρ, f_{model} >40	307 (34)	525	9.7	52.2	21.1	33.1	13 500	13.7
K0 to K400	G1	866 (95)	443	9.3	43.8	24.0	26.5	12 200	16.5
K0 to K400	G2	546 (60)	458	7.6	48.3	18.8	31.8	13 100	12.8
K0 to K400	G3	318 (35)	474	7.0	52.0	16.3	39.2	14 000	10.0
K0 to K400	G4	153 (17)	493	6.1	55.9	14.0	43.2	14 800	8.9
M0 to M400	G1	800 (88)	478	9.8	41.0	31.4	21.6	11 500	20.2
M0 to M400	G2	398 (44)	508	7.8	49.6	21.8	32.9	13 100	14.2
M0 to M400	G4	178 (19)	536	5.8	56.4	16.2	41.1	14 500	8.0

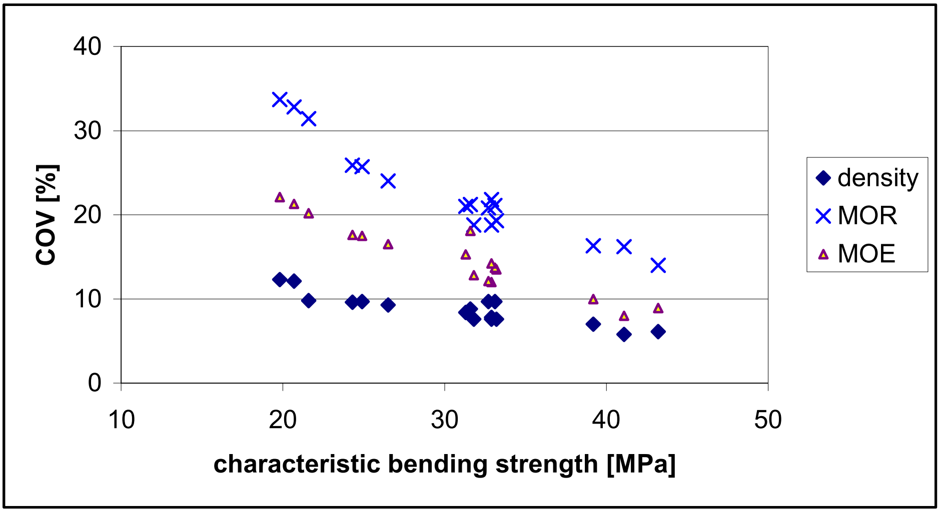


Figure 4. Coefficient of variation of density, modulus of elasticity and bending strength as function of characteristic bending strength of sample.

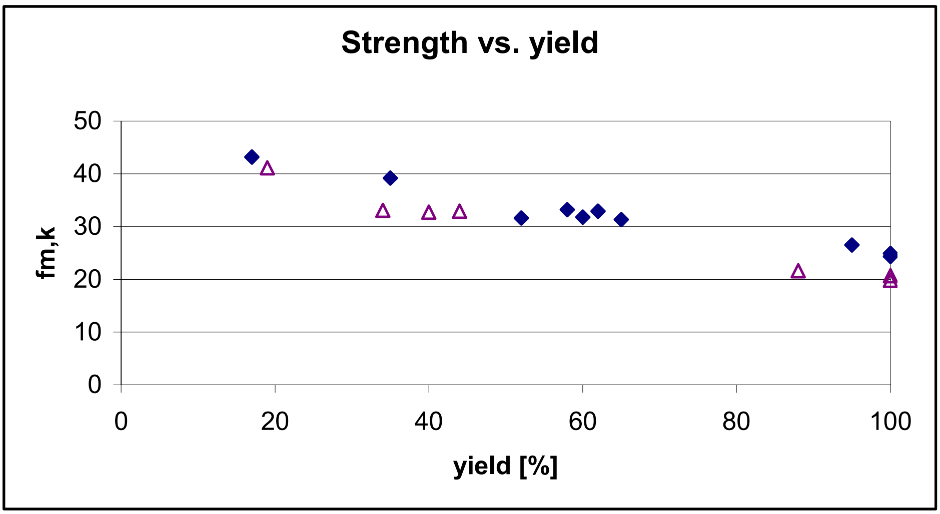


Figure 5. Characteristic bending strength vs. yield received by using different grading methods (Table 6). Open triangles are for pine, filled diamonds for spruce.

2.2 Tension strength and stiffness parallel to grain

2.2.1 Characteristics of unsorted timber

Tension strength of spruce was tested as collaboration of TKK and VTT as part of Combigrade project. Tests were made in accordance with EN408 except that free length of tension specimen was in all cases 2 m. Tested material is characterised in Tables 7 and 8.

Table 7. Sawn timber used in tension tests. Mean values of thickness, b, width, h, moisture content, ω, density, ρ, tension strength, f, and modulus of elasticity, E, are given for each series.

Species	Series	Number	b mm	h mm	ω %	ρ kg/m^3	f N/mm^2	E N/mm^2	Data source
Spruce	K0	115	38	99	12.3	434	34.6	11 900	Combigrade
Spruce	K100	113	50	99	12.7	446	35.1	12 000	Combigrade
Spruce	K200	115	50	150	12.5	441	34.7	12 000	Combigrade
Spruce	K400	114	44	200	12.3	423	29.8	11 200	Combigrade

Table 8. Variation of density, ρ, tension strength, f, and modulus of elasticity, E.

Series	Number	ρ		f		E	
		Mean kg/m^3	COV %	Mean N/mm^2	COV %	Mean N/mm^2	COV %
K0	115	434	10.8	34.6	30.7	11 900	16.3
K100	113	446	10.2	35.1	26.0	12 000	15.8
K200	115	441	9.6	34.7	27.7	12 000	16.0
K400	114	423	9.6	29.8	37.4	11 200	20.3
K0 to K400	457	436	10.2	33.5	30.9	11 800	17.7

2.2.2 Modelling of strength

Equations (4) and (8) were used to model also tension strength, which was size adjusted to reference width 150 mm according to EN384:

$$f_{t,adj} = \left(\frac{h}{150}\right)^{0,2} f_t \tag{9}$$

No adjustment was made to reference length even if the actual free length in tests was 2 m, which is more than nine times the width of specimen specified by EN 408. KAR measurements are made before loading and density of full boards is used as variable in Equation (8). Numerical results are shown in Table 9.

Table 9. Parameters for Equations (4), (8) and (7) obtained for modelling of tension strength of spruce.

Equation	a_0	a_1	a_2	a_3	a_4	**a**	**b**
(4)/(7)	3.46529	0.054676	-0.00531	1.449265		0.8079	-2.63
(8)/(7)	3.41037	-0.1124	0.057898	-0.36526	1.357855	0.827	-3.87

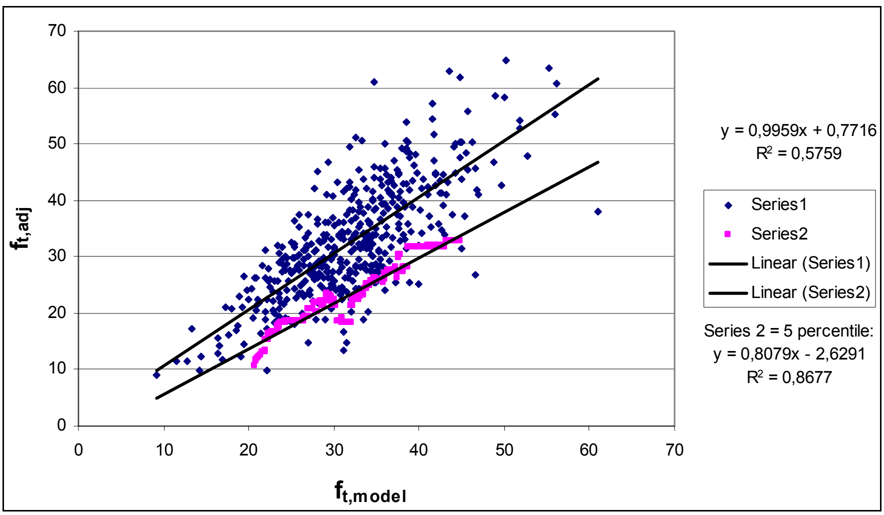


Figure 6. Tension strength vs. modelled strength of spruce based on dynamic modulus of elasticity. Sliding 5 percentiles (series 2) with a fitted trendline are also shown. See Equations (4) and (7) and Table 9.

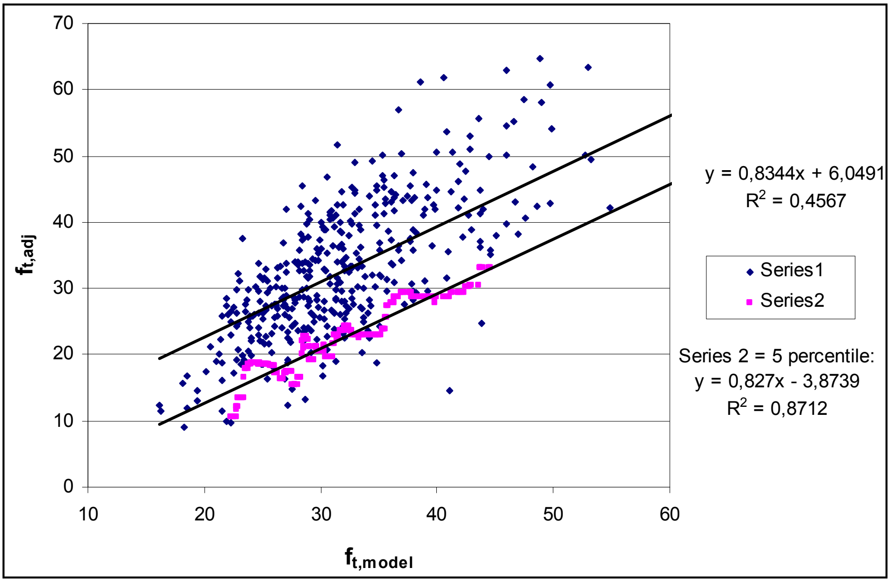


Figure 7. Tension strength vs. modelled strength based on KAR and density. Sliding 5 percentiles (series 2) with a fitted trendline are also shown. See Equations (8) and (7) and Table 9. Four points are outside the picture having $f_{t,model} > 60$ and $f_{t,adj} = 45$ to 50.

2.2.3 Results for graded timber

Artificial grading of the test material was made by the use of models for 5 percentile of tension strength specified by Equations (4), (8) and (7) and Table 9. Additionally a grading was made based on direct application of threshold limits determined for E_{dyn}, KAR and density. Following grades were specified.

1. A-grades based on dynamic modulus of elasticity, Equations (4) and (7):
   grade A1: $f_{t,k\,model} > 25$ MPa
   grade A2: $f_{t,k\,model} > 15$ MPa
   grade A3: 15 MPa < $f_{t,k\,model}$ > 25 MPa
2. D-grades based on KAR and density, Equations (8) and (7),
   grade D1: $f_{t,k\,model} > 23$ MPa
   grade D2: $f_{t,k\,model} > 18.5$ MPa
   grade D3: $f_{t,k\,model} > 14$ MPa

3. X-grade based on exclusion of material with low density or E_{dyn} or with high KAR

   grade X: E_{dyn} >13 000 MPa & KAR < 0.25 & ρ_{12} > 430 kg/m^3.

Characteristics of timber belonging to these grades are shown in Table 10. Results show that grading based on E_{dyn} is slightly more effective in terms of tension strength and yield than grading based on KAR and density. Grade X determined by threshold limits is as good and economic as grade A1 based on E_{dyn}. Relation of yield and characteristic bending strength is illustrated in Figure 8.

Table 10. Density, ρ, tension strength, f, and modulus of elasticity, E, for some samples of graded timber. 5 percentile value is based on nonparametric method. Material includes series K0, K100, K200 and K400 with total N = 457.

Test series	Grade	Yield %	Sample size	ρ Mean kg/m^3	ρ COV %	f Mean N/mm^2	f COV %	f 5 %-tile N/mm^2	E Mean N/mm^2	E COV %
K0 to K400	A1	36	166	472	7.2	41.6	21.6	27.2	14 000	10.2
K0 to K400	A2	92	420	440	9.5	34.6	28.3	19.9	12 400	15.6
K0 to K400	A3	56	254	420	7.8	30.0	24.4	18.4	11 300	12.7
K0 to K400	D1	34	154	467	8.2	41.4	23.3	25.7	13 600	12.8
K0 to K400	D2	65	296	453	8.4	36.9	26.9	22.1	12 900	14.0
K0 to K400	D3	86	392	440	9.7	34.3	29.5	19.0	12 300	16.2
K0 to K400	X	33	136	478	6.6	41.2	20.7	28.2	14 000	10.4

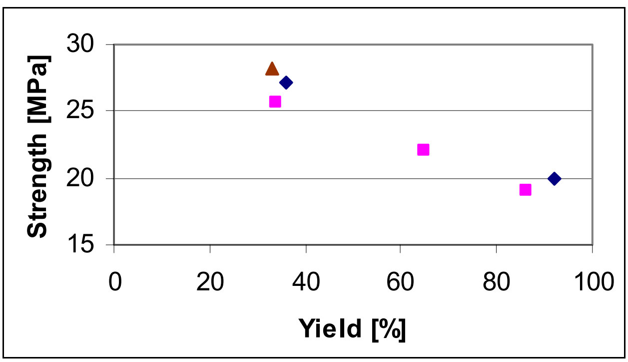


Figure 8. Characteristic tension vs. yield based on Table 10. Squares refer to grades D, triangle to grade X and two diamonds to grades A1 and A2.

2.3 Compression strength parallel to grain

Compression tests were made by TKK. Three dimensions of spruce of Combigrade sampling were tested in compression parallel to grain. Length of test specimen was six times smaller dimension, about 300 mm. Original report of the tests is published by Poussa et al. [2007a and b].

Statistical summary of the results is given in Table 11. In total 403 specimens were tested. Compression strength shows fairly good correlation to density (R^2 = 0.5...0.6), see Figure 9. 282 specimens were visually strength graded according to the Nordic INSTA rules, and most specimens qualified to grade T3 (C30). Reason for high quality is that bending specimens had first been taken from the same planks with intention to include the weakest material in bending specimen, and compression specimen is taken from the remaining part. Results for visually graded material are shown in Table 12. Characteristic values are 30% higher than those given in EN338 for an equivalent grade. Coefficient of variation of compression strength of ungraded material was about 15%.

Table 11. Summary of results in compression parallel to grain.

Test		**50 x 100 2 ex log**	**50 x 150 2 ex log**	**44 x 200 4 ex log**	**All**
N		120	144	139	403
minimum (MPa)	$f_{c,0,min}$	24.3	23.9	21.1	21.1
mean (MPa)	f_{mean}	36.5	38.0	36.2	36.9
maximum(MPa)	$f_{c,0,max}$	47.2	53.5	51.0	53.5
coeff. of variation		0.14	0.15	0.16	0.15
5 percentile (MPa)	$f_{c,0,k}$	27.9	29.2	26.3	27.9
density (kg/m^3)	ρ_{mean}	445.4	438.2	426.1	436.1
coeff. of variation		0.10	0.10	0.10	0.10
mean moisture content (%)	MC	12.3	12.5	12.4	12.4

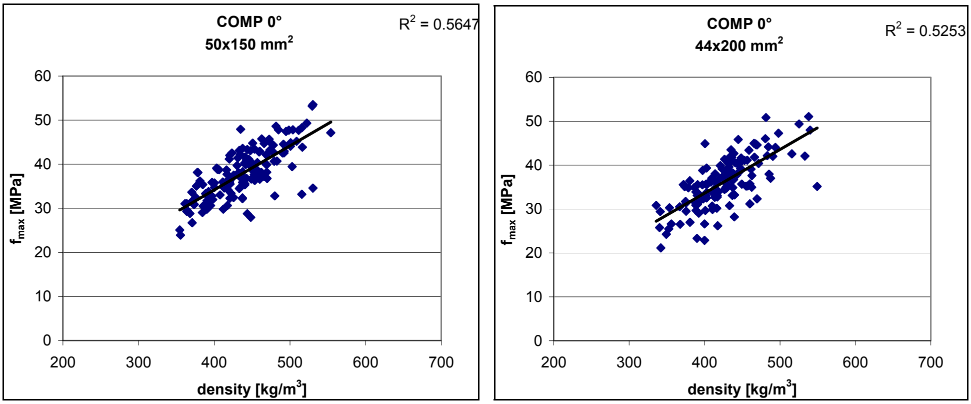


Figure 9. Compression strength of spruce parallel to grain vs. density. Dimensions 50 x 150 and 44 x 200.

Table 12. Compression strength of visually INSTA T-graded spruce compared to EN338 strength values. Characteristic values are calculated also with EN14358-method. For comparison, also values are given for two grades for which 1) modelled compression strength (10) is between 30 and 40 MPa, and 2) above 40 MPa.

	T1/C18	**T2/C24**	**T3/C30**	**Modelled 1**	**Modelled 2**
N	13	58	211	192	67
average [MPa]	30.2	34.0	38.6	36,1	43,1
standard dev. [MPa]	4.2	4.7	5.1	4,0	4,4
$f_{c,0,k}$ nonparametric	24.2	26.2	29.8	29.4	36.5
$f_{c,0,k}$ acc. to EN14358	22.5	26.4	29.4		
$f_{c,0,k}$ in EN338	18	21	23		

Compression strength was modelled as function of density and KAR by using the same type of equation as Glos [Ehlbeck et al. 1985]. We obtained

$$\ln f_c = 2.701029 + 0.002222 \cdot \rho - 0{,}62042 \cdot KAR \qquad (10)$$

where f_c is compression strength in MPa, ρ density in kg/m^3, and KAR total knot area ratio. Observed compression strength vs. modelled strength is shown in Figure 10 and shows $r^2 = 0.64$. Same picture shows also prediction of characteristic value based on sliding 5 percentiles.

Equation (10) was used also to grade test material to grades as follows:

grade 1: modelled compression strength is between 30 and 40 MPa.
grade 2: modelled compression strength is larger than 40 MPa.

This grading resulted in 14 rejects, 192 specimens in grade 1 and 67 specimens in grade 2. Strength values of these grades are included in Table 12.

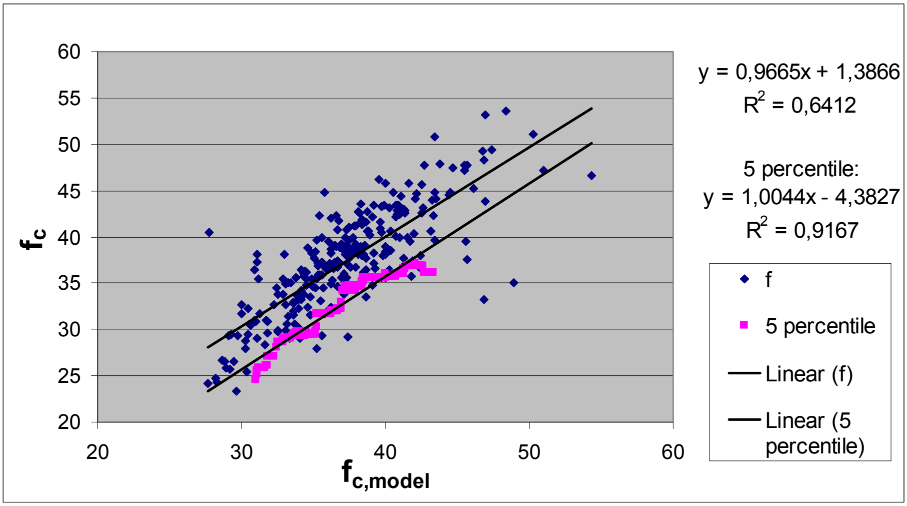


Figure 10. Modelling of compression strength by Equation (10) and sliding 5 percentile values.

2.4 Compression strength perpendicular to grain

Compression tests perpendicular to grain were made according to EN408 and ASTM D143-standards. Additional beam-tests were also made and setups are shown in Figure 11. Tested specimens are listed in Tables 13 and 14. Obtained results are shown in Table 15. Tests were made by TKK and original report is published by Poussa et al. [2007a].

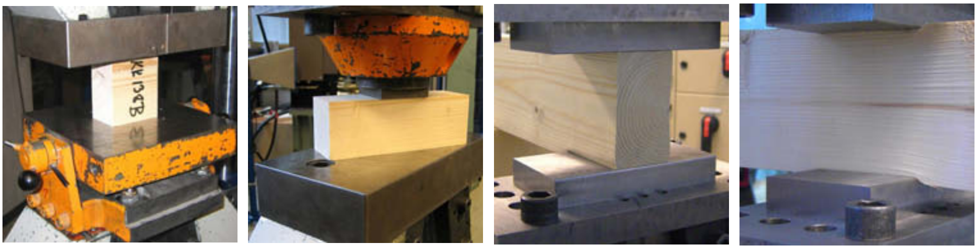


Figure 11. Perpendicular to grain tests. From left to right: EN408, ASTM D 143, beam end, and continuous beam.

Table 13. Perpendicular to grain standard tests.

Test	**Species**	**Pcs.**	**Specimen a x b x length [mm]**	**Standard**	**Loading program**	**Gauge length [mm]**
COMPRESSION 90 DEG, Small size	Spruce	200	45 x 90 x 70	EN408	Deformation controlled. 300 ± 120 s	90
COMPRESSION 90 DEG, Small size	Spruce	200	45 x 50 x 150	ASTM D143	Deformation controlled. max. 2,5 mm	50

Table 14. Perpendicular to grain tests for spruce beams.

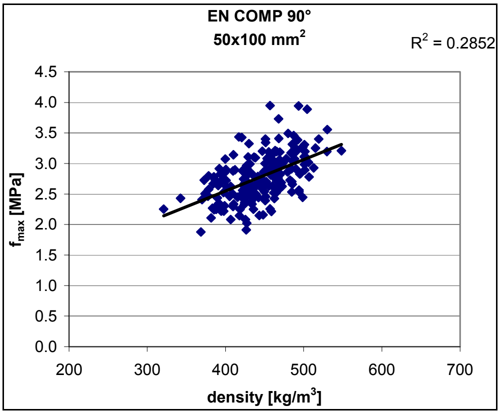
Test	**Pcs.**	**Specimen, a x b x length [mm]**	**Standard**	**Loading program**	**Free distance to beam-end [mm]**	**Gauge length [mm]**
CONTINUOUS BEAM COMPRESSION 90 DEG,	27	45 x 90 x 400	applied EN408	Deformation controlled. 300 ± 120 s	165	90
BEAM END COMPRESSION 90 DEG, Small size	27	45 x 90 x 400	applied EN408	Deformation controlled. 300 ± 120 s	330	90

Table 15. Summary of results in compression perpendicular to grain.

Test		ASTM D143	EN408	BEAM-END	CONTIN. BEAM
N		200	200	27	27
minimum (MPa)		4.8	1.9	2.8	3.7
mean (MPa)		7.0	2.8	3.9	4.7
maximum(MPa)		10.5	4.1	5.0	5.7
characteristic value (MPa)	by ranking	5.2	2.2	-	-
characteristic value (MPa)	by use of prEN14358	5.3	2.2	2.9	3.7
stand. deviation		1.1	0.4	0.5	0.6
coeff. of variation		0.16	0.14	0.14	0.12
av. density (kg/m^3)		441.3	443.0	439.4	434.4
coeff. of variation of density		0.09	0.09	0.10	0.11
av. deformation (mm)		2.5	2.3	2.5	2.4

ASTM standard gave mean strength value 7 MPa, that is 2.5 times larger than the value 2.8 MPa given by EN-standard. Ratio of characteristic values is nearly as big. An obvious reason for higher values in ASTM-test is that surface of test specimen is loaded partially, 50 mm of total length of 150 mm. Test material used has mean density meeting requirement of C24. Characteristic value 2.2 MPa is lower than 2.5 MPa given in EN338 for C24.

Relation of compression strengths determined according to EN408 and ASTM D143 was studied. Specimens are knotless and taken from the same piece next to each other. Correlation analysis between EN and ASTM results gave coefficient of determination $r^2 = 0.49$. Figure 12 shows correlation between density and perpendicular to grain compression strength measured according to both standards. Coefficient of determination is higher for ASTM-results (0.43) than for EN-results (0.29).



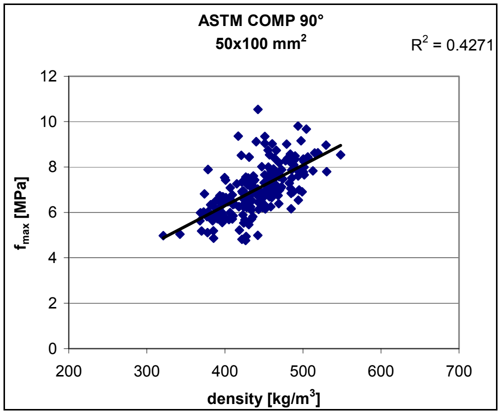


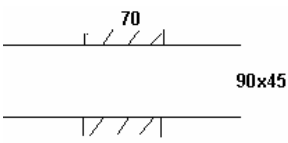
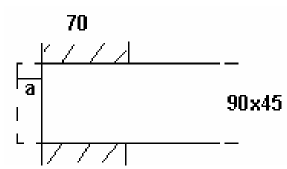
Figure 12. Compression strength perpendicular to grain vs. density for spruce. Upper figure: test in accordance with EM408, lower: ASTM D 143.

In EN408 compression perpendicular to grain strength value is determined using small specimen, which are loaded on the total area. In an actual structural situation, the compressed beam has more load bearing capacity because the adjacent part of beam is not loaded and supports the loaded part. Therefore when designing structures the compression capacity of the beam can be increased. In the old Eurocode pre-standard ENV1995-1-1 factor $k_{c,90}$ is used. The present version EN1995-1-1:2004 and suggested prEN1995-1-1:A1 use effective area A_{ef} which is larger than the actual area.

The ratio of strength capacity of the tested beams to compression strength determined by the standard test EN408 was calculated by using the mean values, because amount of beams tested was only 27 pieces.

Comparison of the obtained ratios when comparing factors of different Eurocode 5 versions with test results is presented in Table 16.

Table 16. Comparison of A_{ef}/A-ratios obtained from test results and different versions of Eurocode.

TEST SETUPS	**Test results** $\dfrac{f_{mean.beam}}{f_{mean.EN408}}$	**prEN1995-1-1:A1 new proposal** $\dfrac{A_{ef}}{A}$	**EN1995-1-1:2004** $\dfrac{A_{ef}}{A}$	**ENV1995-1-1** $k_{c,90}$
	$\dfrac{4{,}7MPa}{2{,}8MPa} = 1.68$	1.85	1.43	1.47
	$\dfrac{3{,}9MPa}{2{,}8MPa} = 1.40$	1.43	1.21	1.0

According to the comparison of ratios presented in Table 16 it is concluded that our results support the suggested changes in prEN1995-1-1:A1. In case of continuous beam, the suggested design capacity of the beam is, however, ten percent higher than our test result. (1.85/1.68 = 1.10).

2.5 Shear strength

Shear tests were made by TKK, and test report is published by Poussa et al. [2007a and b]. Both spruce and pine of Combigrade project were used in tests which were made according to EN408-standard and also by the use of I-beam. Test setups are shown in Figures 13 and 14. Tested specimens are characterised in Table 17. Obtained results are shown in Table 18. We obtained 3.9 MPa for characteristic value of shear strength of spruce in standard test, and 4.2 MPa for pine. Value for spruce is very well in line with earlier result of Glos and Denzler [2003], 3.8 MPa. I-beams gave at least 60% higher shear strength for both spruce and pine. Figure 15 shows that parallel to grain shear strength has no correlation with density. Similar result was obtained for I-beam tests.

Although the test setup was optimized for occurrence of shear failure, 10 percent of spruce and 30 percent of pine beam failures were still bending failures. Bending failures occurred because, avoiding knots at lower flange high-moment area was not realized.

In many cases shear failure took place along the annual rings in web or in flange.

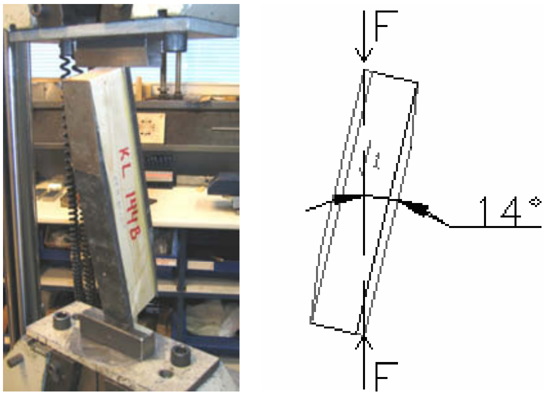


Figure 13. EN408 shear strength parallel to grain test.

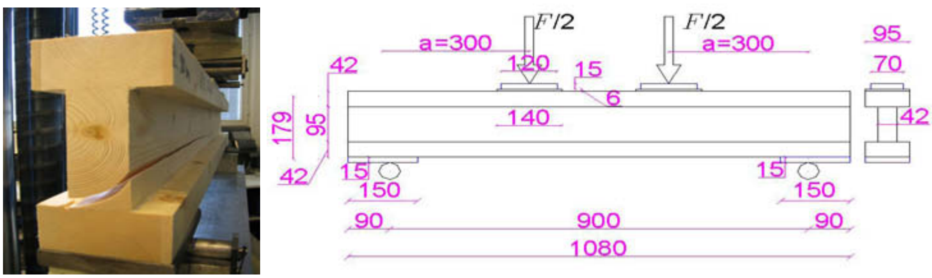


Figure 14. I-beam test for shear strength parallel to grain of web. 4-point bending.

Table 17. Test information.

<table>
<tr><th>Test</th><th>Species</th><th>Pcs.</th><th>Specimen
a x b x length [mm]</th><th>Standard</th><th>Loading program</th></tr>
<tr><td rowspan="2">SHEAR
0 DEG,
Small size</td><td>Spruce</td><td>100</td><td rowspan="2">32 x 55 x 300</td><td rowspan="2">EN408</td><td rowspan="2">Deformation controlled.
300 ± 120 s</td></tr>
<tr><td>Pine</td><td>100</td></tr>
<tr><td rowspan="2">SHEAR
I-BEAM
0 DEG,
Structural size</td><td>Spruce</td><td>40</td><td rowspan="2">web 42 x 95 x 1080
flange 42 x 95 x 1080</td><td rowspan="2"></td><td rowspan="2">Deformation controlled.
300 ± 120 s</td></tr>
<tr><td>Pine</td><td>40</td></tr>
</table>

Table 18. Summary of results.

Test		EN408-shear	EN408-shear	I-BEAM-shear	I-BEAM-shear
species		spruce	pine	spruce	pine
N		100	119	40	40
minimum (MPa)		3.2	3.3	6.6	6.4
mean (MPa)		5.2	5.6	8.3	8.6
maximum(MPa)		6.7	8.6	9.6	9.9
characteristic value (MPa)	by ranking	3.9	4.2	-	-
characteristic value (MPa)	by use of prEN14358	3.9	4.1	7.2	7.2
stand. deviation		0.8	0.9	0.6	0.8
coeff. of variation		0.15	0.16	0.08	0.09
av. density (kg/m3)		445.9	443.5	417.2	443.7
coeff. of variation of density		0.15	0.11	0.14	0.09

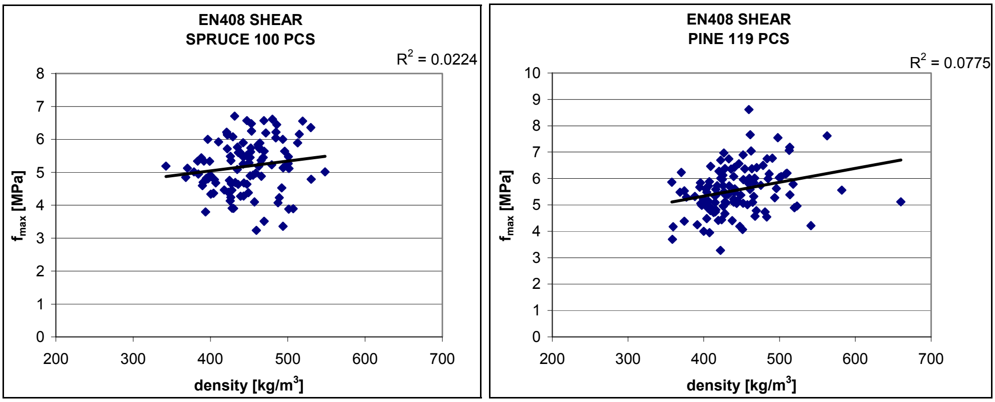


Figure 15. Shear strength vs. density for spruce (left) and pine (right).

3. Round timber

3.1 Old results

It is known that bending strength of round timber is fairly high. Some results of an old, unpublished Finnish research are shown in Figures 16 and 17 indicating a clear dependence on knot size. In Finnish building code, a characteristic bending strength of 30 MPa has traditionally been used for pine and spruce round timber, when no other information is available. According to Figures 16 and 17 this seems appropriate, when maximum knot diameter is not larger than 40 mm, or KAR (ratio of the sum of knot diameters to the circumference of the log) is less than 0.2. These results are based on testing of round pine timber which has diameter of about 250 mm.

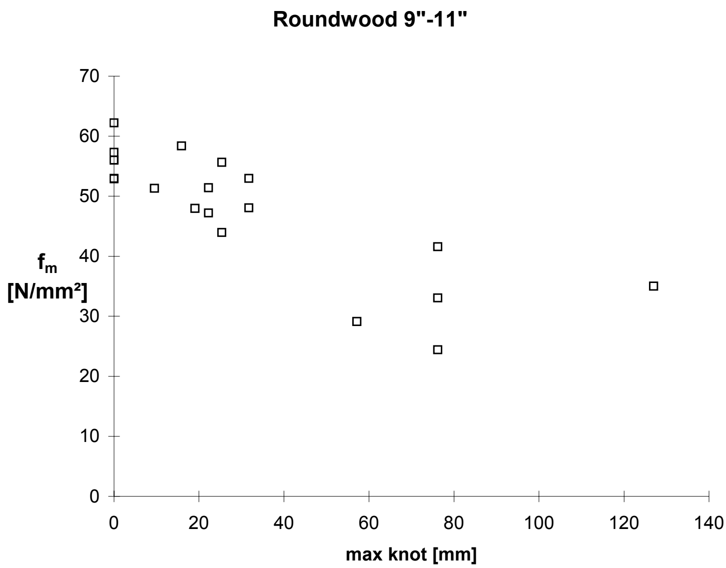


Figure 16. Bending strength of seasoned pine logs tested in 1950s vs. knot size.

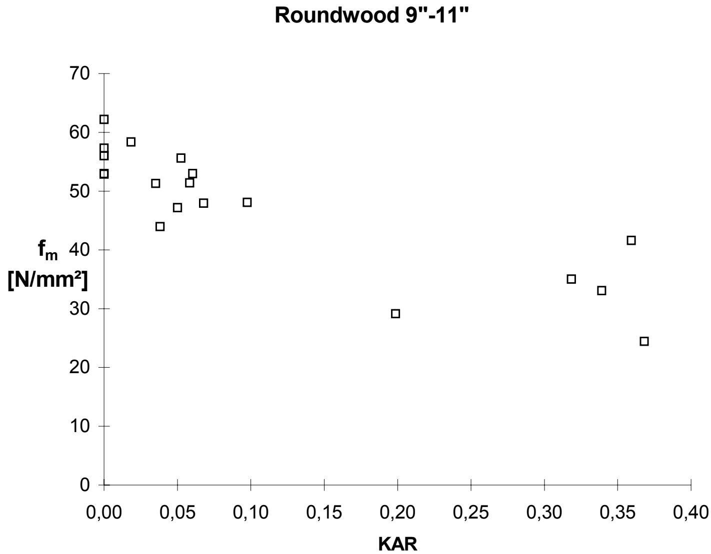


Figure 17. Bending strength of seasoned pine logs tested in 1950s vs. KAR.

3.2 Small diameter timber

A large European project (FAIR CT 95-0091) was conducted on the use of small diameter round timber in construction. Final report of project includes not only strength of material but also aspects related to economy of harvesting in thinnings, drying, oil impregnation, development of feasible structures and connections [Ranta-Maunus 1999]. This publication repeats the main conclusions concerning strength values. Much more details can be found in the final report and in several published detailed reports such as a CIB W18 paper [Ranta-Maunus et al. 1998].

Small diameter (80 to 150 mm) round wood could have lower strength than mature logs, because it is, to a large extent, juvenile wood. On the other hand, the small size suggests that small diameter wood could have higher strength than large diameter timber. Next chapter describes results obtained for small diameter round timber.

3.2.1 Characteristics of test material

Small-diameter round timber studied here consists of spruce (*Picea abies* and *Picea sitchensis*) and pine (*Pinus sylvestris*). Spruce was sampled from two locations in Finland, two locations in Austria and one location in the United Kingdom. Pine was sampled from four locations in Finland and one location in the United Kingdom.

Bending and compression parallel to the grain tests were carried out following, as closely as possible, the test method given in EN 408. In addition to bending strength and modulus of elasticity (true), the density and moisture content were determined.

Before analysis, all individual density values were adjusted to a moisture content of 12% according to EN 384. No other adjustments were carried out.

A summary of the results is given in Table 19. The mean diameter of the specimens was 123 mm. The mean moisture content of the specimens was 16.1%. This results in lower strength and modulus of elasticity values than those of specimens of 12% moisture content.

Table 19. Density, ρ, bending strength, f, and modulus of elasticity, E, of unsorted small-diameter round timber sampling.

Property	Number	ρ		f		E	
		Mean kg/m^3	COV %	Mean N/mm^2	COV %	Mean N/mm^2	COV %
Bending	660	467	12.7	56.2	21.3	12 300	26.4
Compression	575	469	13.2	26.9	23.3	10 700	28.3

3.2.2 Results for visually graded material

Based on the statistical analysis of strength data performed by the different project participants, a selection of visual strength-grading parameters was made: maximum knot-size per diameter, knot sum per diameter and maximum growth ring width, and limits for these parameters were set. A synopsis of the grading criteria based on this research is given in Table 20.

Table 20. Definition of visual grades for round Scots pine and Norway spruce.

Strength-grading criteria	**Grade A**	**Grade B**
Knot sum per diameter ks/d [%]	75	100
Max. knot per diameter mk/d [%]	25	30
Ring width r [mm]	3	5

The grading criteria specified above were applied to the tested samples of Scots pine and Norway spruce from Finland. Norway spruce had an initial sample size 200, of which 143 bending specimens and 149 compression specimens fulfilled the limits of grade A. The unsorted material met strength class C30 requirements except for density, which met C18. Obviously, density is the critical factor which determines the strength class. This material was divided into 3 samples according to the moisture content of specimens. In Table 15 the results are summarized: number of specimens meeting grading criteria, and mechanical characteristics of the sample. Because so many spruce specimens passed grade A limit, sorting was not carried out for grade B.

UK Scots pine material had 100 specimens in bending and compression. Finnish Scots pine material had 150 machine-debarked specimens in bending and compression. The unsorted material suggested that C30 is possible but compression strength is difficult to achieve. Of this material, 70 UK and 52 Finnish bending specimens, and 73 UK and 47 Finnish compression specimens passed the limits of grade A, and 127 Finnish bending specimens and 119 compression specimens passed the limits of grade B given in Table 20, when grade B includes also the high quality specimens which are qualified to grade A.

The 5-percentile values of the samples are determined by the following methods:

- For strength properties $f_{c,\,0}$ and f_m a non-parametric method is used, i.e. it is a test value for which 5 % of the values are lower. If this was not an actual test value, then interpolation between two adjacent values was permitted.
- For ρ it was calculated from a normal distribution: ρ_{05} = (Mean ρ_{12} - 1.65*s), where s is standard deviation for the sample.

*Table 21. 5-percentile values of graded round-pole samples in **bending**, adjusted to 12% MC in accordance with EN 384 except for size adjustment.*

Grade	Sample	Mean d [mm]	Mean MC [%]	Sample size	ρ_{05} [kg/m^3]	$f_{m,05}$ [N/mm^2] by rank	$E_{m,mean}$ [kN/mm^2]
A	FIN spruce 1	100	13.5	47	394	45.0	12.9
A	FIN spruce 2	117	14.6	48	368	52.5	12.8
A	FIN spruce 3	115	19.2	47	411	46.2	14.1
A	FIN pine	117	14.7	52	433	38.3	12.5
A	UK pine	127	19.1	70	466	41.9	15.4
B	FIN pine	126	15.2	127	416	35.2	11.8

*Table 22. 5-percentile values of graded round-pole **compression** samples, adjusted to 12% MC in accordance with EN 384 except for size adjustment.*

Grade	Sample	Mean d [mm]	Mean MC [%]	Sample size	ρ_{05} [kg/m^3]	$f_{c,05}$ [N/mm^2] by rank
A	FIN spruce 1	100	13.8	49	381	28.2
A	FIN spruce 2	100	14.6	50	389	29.6
A	FIN spruce 3	108	18.7	50	362	25.1
A	FIN pine	124	11.1	47	434	28.6
A	UK pine	126	17.4	73	462	26.8
B	FIN pine	123	13.8	119	404	21.7

The equivalence between the visual grades and strength classes is considered on the basis of the results summarized in Tables 21 and 22. A timber population may be assigned to a strength class, when characteristic values of E_m, f_m and ρ at 12% moisture content are greater or equal to the limits given in EN338. Compression strength is also considered as a strength classification criterion, in addition to the requirements of CEN 384. As a result, it is concluded that grade A Scots pine and Norway spruce meet the requirements of C30 and grade B Scots pine C18 (Table 23).

The characteristic value of strength for a population in a grade, f_k, is calculated in accordance with EN 384 to be:

$$f_k = f_{05} k_s k_v \tag{11}$$

where f_{05} is the weighted mean of the sample's fifth percentile values, k_s is a factor relative to the number of samples and their size, and $k_v = 1$ for visual grading.

The characteristic value of ρ is calculated as the mean of the sample's fifth percentile values weighted by sample sizes, and the mean value of E is the mean of the sample's mean values weighted by sample sizes, without consideration of Equation (11).

Comparison of bending strength of 250 mm diameter poles in Figures 16 and 17 and results for small diameter poles suggests that grade A defined based on small diameter timber data could be applied also for larger size poles, and strength class C30 can be applied for different size round timber.

Table 23. Characteristic values obtained for graded populations and suggested strength classes.

Species country	**Grade**	k_s	$f_{m,k}$ [N/mm^2]	$f_{c,k}$ [N/mm^2]	$E_{m,mean}$ [kN/mm^2]	ρ_k [kg/m^3]	**Strength class**
Norway spruce (FIN)	A	0.91	43.6	25.1	13.3	384	C30
Scots pine (FIN, UK)	A	0.84	33.9	23.1	14.0	450	C30
Scots pine (FIN)	B	0.86	30.2	18.7	11.8	411	C18

4. Glued laminated timber

4.1 Tension strength perpendicular to grain

Two different projects have been executed to determine the duration of load effect on tension strength perpendicular to grain in different sized curved beams exposed to cyclically varying humidity. The earlier project (VTT) was carried out 1991–1993 and was reported by Ranta-Maunus and Gowda [1994]. The later, more comprehensive project (AIR) was completed in 1997 and was reported by Gowda et al. [1998]. As part of the AIR-project, tensile tests with specimen volumes of 0.01 and 0.03 m^3 were made by FMPA in Germany [Aicher et al. 1998]. The curved beam test series are summarised in Table 24. Loading configuration is illustrated in Figure 18. The distance between loads, *l*, is given in Table 24 as a characteristic dimension with regard to the length effect. The radius of curvature of the centre line of beam was at VTT tests about 3 m and at AIR tests 5.7 m.

Table 24. Dimensions of curved glulam test specimens.

Test series	Specimen dimensions (mm)	*l* (mm)	Loading type	Conditions
VTT S1+S3	90 x 400 x 4300	1000	short term + step wise long term	cyclic RH 40 <-> 85%
VTT S2	90 x 400 x 4300	1000	step wise long term	cyclic RH painted
AIR S1	90 x 600 x 5400	2000	short term	65% RH
AIR S2	90 x 600 x 5400	2000	step wise long term	cyclic RH 55 <-> 90%
AIR S3	90 x 600 x 7400	4000	short term	65% RH
AIR S4	90 x 600 x 7400	4000	step wise long term	85% RH
AIR S5a	140 x 600 x 7400	4000	short term	65% RH
AIR S5b	140 x 600 x 7400	4000	short term	85% RH
AIR S6	140 x 600 x 7400	4000	step wise long term	cyclic RH 55 <-> 90%
AIR S8	140 x 600 x 7400	4000	step wise long term	85% RH

Spruce material used in tensile experiments was the same as in curved beams (AIR). One difference in long term experiments was that the tensile specimens were conditioned at 65% RH before experiments whereas curved beams were conditioned at the average humidity of anticipated cyclic conditions. As a result, the first wetting cycles were more severe in tension tests than in curved beam tests. In tensile experiments and in earlier VTT tests, the long term load was applied by hanging loads (lever arms) whereas in the later tests (AIR) on curved beams the load was applied by a spring system.

All experiments were carried out under a stepwise increasing load, one step lasting 28 days. It was assumed that this kind of medium term load duration is most relevant for timber structures. For roof structures, the snow load is dimensioning in northern countries. Even if the cumulative action of snow load has much longer duration, the design loads are based on maximum snow load over 50 years, and 4 weeks is a reasonable estimate for the time the load exceeds 90% of the design value. Each test series had 6 or 8 specimens.

The results of the experiments carried out at VTT and FMPA are summarised in Table 26 and discussed by Aicher et al. [1998] and Ranta-Maunus [1998, 2001].

Figure 18. Short term reference tension test of FMPA (left) and bending test of VTT (right).

4.1.1 Short term test results

Short term experiments of curved beams have been originally reported by Gowda and Ranta-Maunus [1993 and 1996]. A compilation of both short and long term test results is given in Table 26.

The strength results indicate no clear dependence on moisture content, in fact the values at higher moisture content are somewhat higher than the ones with lower moisture content. However, the results in test series 5a and 5b with different moisture contents have been combined. The cumulative distributions of short term strength are illustrated in Figure 19. The Normal, lognormal and Weibull distributions are fitted to the results of AIR-programme and estimated characteristic values are given in the Table 25.

The obtained lower 5% fractile of tension strength perpendicular to grain was in VTT test series 0.95 N/mm^2 based on 18 curved beams, and in AIR test series from 0.46 to 0.72 N/mm^2 depending on the size of beam.

Table 25. Five and fifty percent fractile values obtained for tensile strength perpendicular to grain (N/mm^2) by fitting 2-parameter Weibull, normal and lognormal distributions to the curved beams results.

Fractile	**Test series S1**			**Test series S3**			**Test series S5**		
	Normal	**Log-normal**	**Weibull**	**Normal**	**Log-normal**	**Weibull**	**Normal**	**Log-normal**	**Weibull**
50 %	0.838	0.835	0.848	0.719	0.717	0.706	0.600	0.595	0.611
5 %	0.731	0.736	0.716	0.632	0.635	0.596	0.472	0.481	0.464

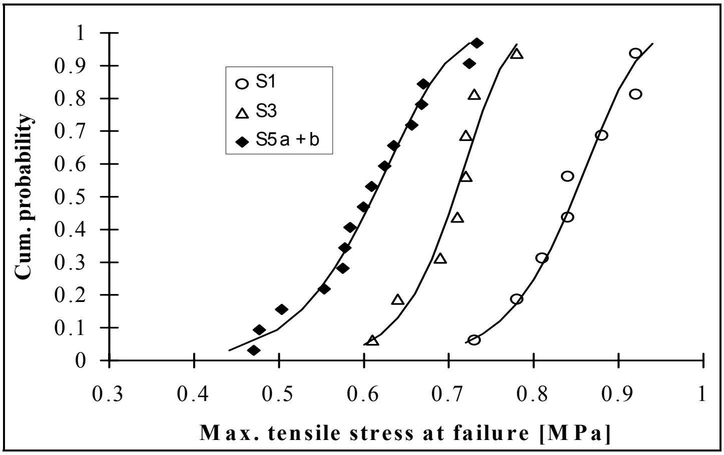


Figure 19. Cumulative distributions of all short term strength values with curved glulam: observations and Weibull fitting.

4.1.2 Long term test results

Long-term loading test results are given as ratio of load at failure to estimated ramp load value, based on ranking method. Method is illustrated by Figure 20 which shows cumulative distributions of load duration tests (points) and reference short term strength distribution (curve). Duration of load factor is calculated as ratio of observed maximum stress at long term test to reference value at same cumulative probability level. Furthermore, the effect of load duration is separated from effect of moisture variation. The effect of moisture variation is considered to be primarily a short term effect caused by increased loading in form of moisture induced stresses perpendicular to grain. Two calculated stress distributions through thickness are shown in Figure 21. Most failures were observed when the moisture cycling caused high tensile stresses in the internal part of beam.

Numerical values of duration of load effect, k_{DOL}, were observed as follows:

- at constant humidity tests, values were in range k_{DOL} = 0.70 to 0.77, when time to failure was 2 to 4 weeks at that load level
- at cyclic humidity test k_{DOL} = 0.76 was achieved when the beams were surface coated with alkyd paint

– at cyclic humidity tests the values ranged k_{DOL} = 0.45 to 0.66 when beams were not surface treated

– at natural sheltered environment in Stuttgart the value k_{DOL} = 0.65 was received whereas similar tension specimens gave 0.50 in cyclic test and 0.75 at constant humidity.

In all cases the lowest k_{DOL}-value was obtained with the thinner tension specimen and largest value with beam specimens.

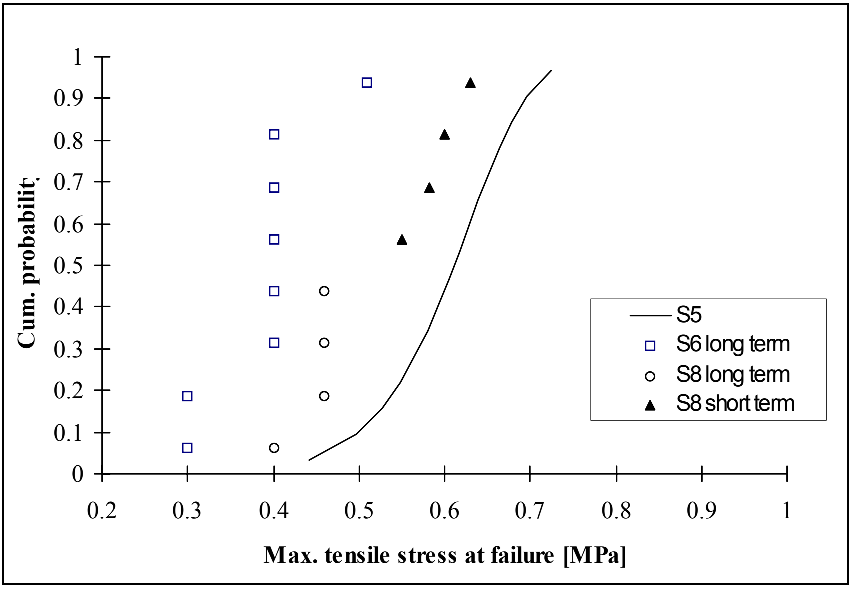


Figure 20. Cumulative plot of long term strength results (points) with short term strength reference curve (S5 is reference curve for S6 with cyclic humidity and S8 with constant humidity). S8 short term refers to residual strength after long term loading.

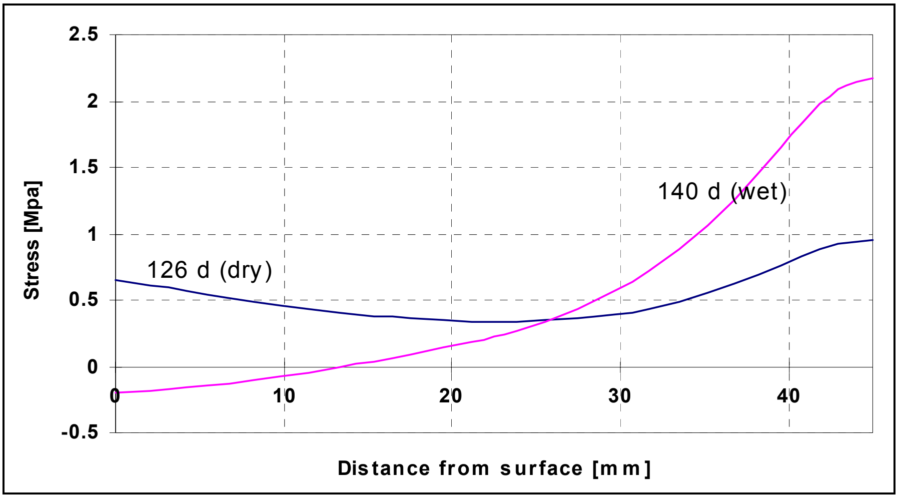


Figure 21. Calculated stress distribution for half thickness of beam in test series AIR-S2 after dry period (126 d) and wet period (140 d).

Table 26. Compilation of major ramp and DOL test results on tension strength perpendicular to the grain of glulam obtained with curved beams and structural sized tension specimens [Aicher et al. 1998].

Test and specimen configurations			Units	Results of different test series at VTT and FMPA: Tension specimens AIR 01a–d	Tension specimens AIR 03a–d	Curved beams VTTS1/2/3[1]	Curved beams AIR S1/2	Curved beams AIR S3/4	Curved beams AIR S5/8/6
Specimen characteristics	(Apex) volume	V	m^3	0,01	0,03	0,036	0,108	0,216	0,336
	lamella thickness	d	mm	33	33	16	33	33	33
	lamella width	b	mm	90	140	90	90	90	140
	mean density	ρ_{mean}	kg/m^3	530	493	470	496	503	493
Ramp load results	test series			AIR 01a	AIR 03a	S1	AIR S1	AIR S3	AIR S5
	sample size		–	44	44	12	8	8	16
	mean moisture content		%	12	12	12,3	11,6	11,4	12–15
	$f_{t,\,90,\,mean}$		N/mm^2	0,89	0,67	1,21	0,85	0,71	0,61
	$f_{t,\,90,\,05}$		N/mm^2	0,74	0,55	0,95	0,72	0,59	0,46
Duration of load results **Constant climate**	test series			AIR 01b	AIR 03b	S2		AIR S4	AIR S8
	relative humidity		%	65	65	40–85[2]		85	85
	mean moisture content		%	12	12	11–12[2]		18	18
	sample size		–	15	15	6		8	8
	$k_{DOL,\,mean}$		–	0,70	0,75	0,76		0,87	0,77
	time to failure for sample mean	$t_{F,\,mean}$	d	22	24	13		4	14
	$k_{DOL,\,mean,\,exrapolated\ for\ 6\ months\ load\ duration}$		-	0,64	0,70	0,70		0,82	0,71
Cyclic climate	test series			AIR 01c	AIR 03c	S3	AIR S2		AIR S6
	relative humidity span (RH)		%	55–90	55–90	40–85	55–90		55–90
	cycle length		d	28	28	28	28		28
	conditioning before cycling (RH)		%	65	65	70	75		75
	sample size		–	15	15	12	8		8
	$k_{DOL,\,mean}$		–	0,45	0,50	0,55	0,60		0,66
	time to failure $t_{F,\,mean}$		d	17,5	18,5	20	28		15
Natural sheltered outdoor climate	test series			AIR 01d	AIR 03d				
	relative humidity span (RH)		%	35–95	45–90				
	temperature span		°C	-5–22	2–22				
	conditioning before loading (RH)		%	65	65				
	sample size		–	15	15				
	$k_{DOL,\,mean}$		–	0,60	0,65				
	time to failure $t_{F,\,mean}$		d	2,6	24,5				

[1] Different material tested in earlier test series preceding AIR project

[2] Beams coated with alkyd paint

4.1.3 Analysis and discussion

The results show a clear volume effect: tensile strength perpendicular to grain depends on the width and length of the curved beam, as explained in the test reports. The apparent volume effect is stronger in short term ramp loading than in long term loading. When the results for tensile specimens are compared to curved beams, it is observed that beams are stronger than can be predicted based on tensile experiments: a curved beam has the same strength as a tensile specimen if the volume of constant moment span is about 9 times the volume of the tensile specimen. Based on a parabolic vertical stress distribution in beams, we would expect that the beam volume being nearly 3 times the volume of the tension specimen, strength would be equal. The other way of adjusting beam values for compatibility with tensile test is to divide stresses by factor k_{dis}, as has been done in Eurocode 5. In Figure 22 failure stresses of beams have been divided by factor $k_{dis} = 1.85$, which together with the volume effect exponent of 0.2 gives a good fit of tensile and beam results obtained in long term testing at constant humidity. This suggests that it would be justified to use $k_{dis} = 1.85$ in structural design instead of $k_{dis} = 1.4$ given in Equation (6.52) of Eurocode 5 (EN1991-1-1).

The cyclic moisture content results are not exactly comparable, because tensile tests were subjected to a stronger moisture change. Short term loading results for curved beams show a larger volume effect with exponent 0.3.

The difference in strengths between curved beams and tensile specimens cannot be fully explained. Compression stresses perpendicular to grain in areas subjected to load will decrease the volume where tensile stresses perpendicular to grain are close to nominal value. However, this effect alone is not assumed to explain the difference.

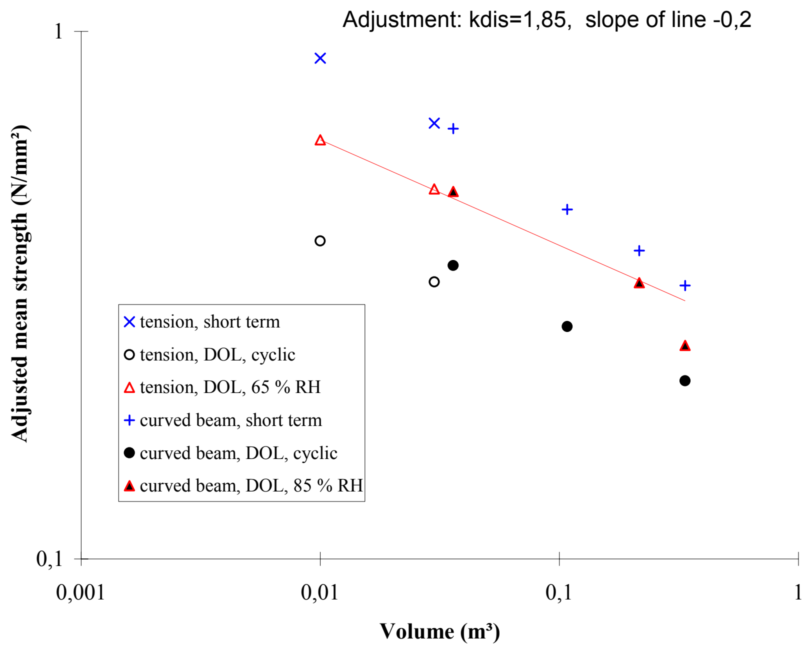


Figure 22. Strength perpendicular to grain vs. volume on double logarithmic scale. Curved beam strength is divided by 1.85. Slope of line corresponds to a volume effect exponent 0.2.

5. Creep deflection of structural size beams

This chapter reports creep experiments in heated room conditions which have not been reported earlier for the full period of 16 years of loading. Also results of experiments in unheated building conditions, which have been reported earlier [Gowda et al. 1996, Ranta-Maunus and Kortesmaa 2000] are summarised as well as creep experiments of glulam beams exposed to uncontrolled weather conditions in 1960's [Ranta-Maunus 1975].

5.1 Creep in heated room

In order to study creep of timber at low load levels close to the effect of dead load of roofs in Nordic countries, creep experiment of 8 glued laminated beams was started in June 1991 in heated indoor environment, and test continued until 2007. Modulus of elasticity of beams range from 13 200 to 14 400 MPa and density from 474 to 502 kg/m^3. Glulam beams have cross-section 90 x 270 mm^2, span 9 m and are made from spruce lamellae, and have a varnished surface. Loading consists of own weight of the beams and two point loads of 1840 N or 614 N each, being located symmetrically at distance of 2 m from each other. The maximum bending stress of 4 beams is 4 MPa and 2 MPa for the remaining 4 beams. More information of these creep experiments is published by Ranta-Maunus and Kortesmaa [2000].

Variation of relative humidity in the test room is demonstrated in Figure 23. Temperature was in range of 19 to 23, mainly 20 to 22 °C in test room which was on lowest level of VTT underground research hall.

Creep curves of glulam in heated room under low load level during 16 years are shown on Figure 24. The main result is that creep has not fully stopped during 16 years, but continues very slowly. Relative creep at the two load levels are similar. During first 8 years annual variation of relative deflection is shown, whereas during later years, measurement is made only once a year or more seldom. It is essential, that creep values are measured during the same season when we want to draw conclusions on the long term trend of creep. Otherwise effects of annual moisture cycling will complicate the analysis.

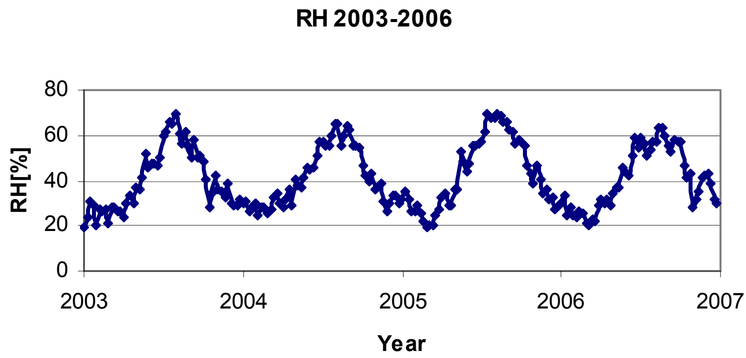


Figure 23. Weekly mean values of relative humidity in heated test room 2003–2006.

We can conclude that creep is 40% of elastic deformation after the first year, 60% in about 4 years increasing very slowly after that reaching 70% in 16 or 20 years. A simple creep curve

$$\frac{w(t)}{w(0)} = 1 + 0.4t^{0.2} \tag{12}$$

where t is time in years, seems to fit well to the long term trend as demonstrated in Figure 25. Experimental values are based on readings during summers, except the value after 6 months loading.

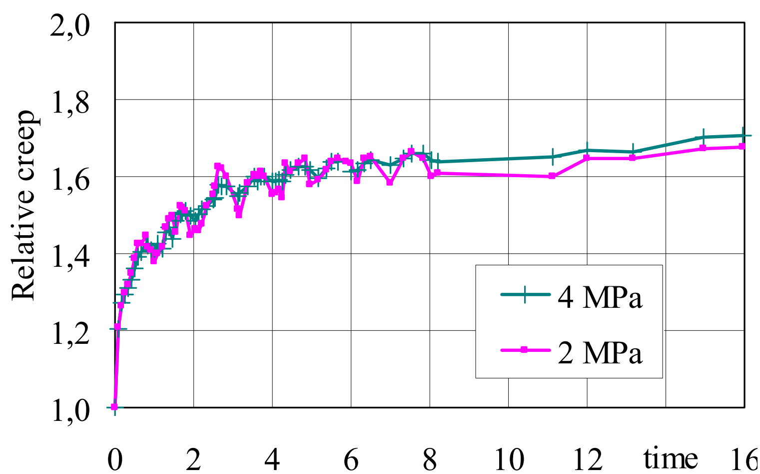


Figure 24. Relative creep deflection (means of 4 beams) of spruce glulam in heated room under low load levels (2 and 4 MPa). Time is given in years.

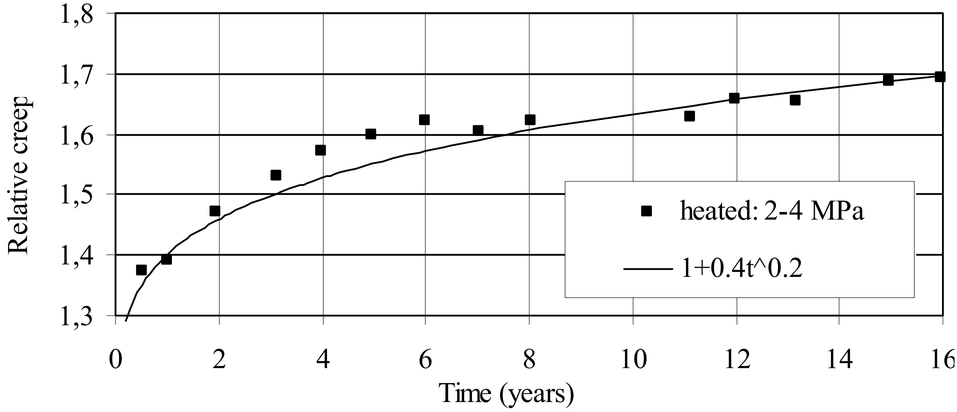


Figure 25. Relative creep deflection (mean of 8 beams) of spruce glulam in heated room under low load levels (2 and 4 MPa) and simple creep curve (12).

5.2 Creep in unheated room and outdoors

Bending creep experiments made in sheltered environment conditions are summarised in Table 27 which gives relative creep values after full years. Some experiments were stopped early because of a large lateral deflection of beams. Nonlinearity of creep seems to begin at low load levels: 7 MPa gives clearly larger relative creep than 2 MPa, whereas difference between 4 and 2 MPa is minimal.

Relative creep in heated room and in sheltered room conditions in Southern Finland are equal. Surface coating and impregnation treatment which prevents moisture cycling in wood decreases creep deformation. Table 27 shows that surface coating with emulsion paint decreases relative creep 30%, alkyd paint 50% and creosote impregnation 70% whereas CCA treatment did not decrease creep. The old experiments under exposure to weather show twice as high relative creep deformation as under sheltered environment under similar stress level.

Table 27. Summary of relative creep deformation of specimens under long term loading in sheltered environment. All values are averages of 4 structural size beams. Some old results of glulam beams from 1960´s are also included, which are exposed to weather [Ranta-Maunus 1975].

Relative creep of specimens										
Test material	**Dimension [mm]**	**Surface treatment**	**Max. stress MPa**	**Time (years)**						
				1	**2**	**3**	**4**	**5**	**6**	**7**
Pine	50 x 150 x 5000	none	7	1.62	1.69	1.79	1.84	1.90	1.91	0.97
		emulsion	7	1.46	1.52	1.57	1.60	1.62	1.64	
		alkyd	7	1.31	1.35	1.40	1.41	1.45	1.45	
		creosoted	7	1.19	1.22	1.27	1.28	1.27	1.27	0.28
		CCA	7	1.58	1.64					
Spruce	50 x 150 x 5000	non	7	1.66	1.76					
		treated	2	1.42	1.44	1.50	1.52	1.55	1.58	1.60
Glulam, spruce	90 x 180 x 6500	non treated	2	1.44	1.48	1.57	1.61	1.62	1.65	1.65
Glulam, spruce, 1960's	150 x 220 x 7600	plastic cover, outdoors	5.4	1.65	1.88	2.0	2.0	2.1		
Glulam, pine, 1960's	95 x 176 x 7080	plastic cover, outdoors	8.2	1.75	1.9	2.0	2.1	2.2		
Glulam, pine, 1960's	95 x 176 x 7080	exposed, outdoors	8.2	2.0	2.3	2.5	2.6	2.8		
Kerto-LVL	51 x 200 x 6500	non treated	2	1.67	1.69	1.85	1.90	1.96	1.96	1.99
I - beam	45 x 45 flange 6,5 web	non treated	3	1.68	1.78	1.92	1.95	1.98	1.98	1.98

6. Summary

This report is a compilation of test results and their analysis covering a wide area of materials and loading conditions. The main function of this publication is to document valuable numerical results for future use.

The characteristic bending strength of unsorted Nordic spruce sawn timber is traditionally considered to be 26 MPa. In Combigrade project sampling where no logs were rejected because of low quality, the five percentile of bending strength was 24 MPa, and that of tensile strength 18 MPa. Five percentile of bending strength of pine was 20 MPa. However, these high five percentile values do not justify to deliver ungraded timber for structural use, because weak pieces need to be sorted out.

It was observed that bending strength of both spruce and pine timber has a positive correlation with width of beam (Tables 3 and 4). Therefore it is suggested that strength models used as basis for determination of settings of grading machines should include dimensions of sawn timber as variables. These results support the height effect used in European standards (exponent = -0.2). Especially the results obtained for spruce are close to standard approach.

Tension strength of sawn timber, especially in better grades, is higher than 60% of bending strength specified in EN338. A proposal based on results obtained for five percentiles in Chapter 2.2 is given in Table 28. For grades missing in Table, tension to bending ratios can be interpolated. Tension to bending strength ratio ranges from 0.65 for C16 and lower to 0.75 for C50.

Table 28. Suggestion for new tension strength values for EN338.

	Suggested tension to bending ratio	**Suggested f_{tk}**	**Present EN338**
C16	0,65	10	10
C20	0,68	14	12
C24	0,70	17	14
C30	0,72	22	18
C40	0,74	30	24
C50	0,75	37	30

Figure 4 illustrates nicely that variability of mechanical properties of sawn timber decreases when grade increases. The clear trend is that the coefficient of variation decreases when the characteristic strength increases. COV of bending strength, modulus of elasticity and density of grade C40 is only half of the COV values for C18. In European standardisation there are more strict requirements for strength classes C35 and higher:

– daily mechanical testing in production is required only for C35 and higher, and
– 12% decrease of strength requirement is applied for machine graded timber of C30 and lower.

In light of Figure 4 harder requirements applied to higher grades seem not justified.

Grading methods are compared in Chapter 2. The results support the earlier understanding that stiffness is the best predictor of strength. An optimised yield to grades cannot be obtained without measuring stiffness, e.g. dynamic modulus of elasticity. When grading glulam lamellas based of tension strength, density should be also measured because it has effect on strength of finger joints. Setting of threshold values for density and knot sizes should be part of lamella grading procedures. A remaining challenge in strength grading is to improve detection of weak pieces which have defects such as top failures.

Compression strength values obtained for spruce graded visually simultaneously to C24 and C30 were 30% higher than those given in EN338. This suggests that EN338 values are quite conservative.

Compression strength perpendicular to grain determined according to EN408 was lower than given in EN338 for a grade with same density (2.2 vs. 2.6 MPa). However, severe structural failures caused by compression stress perpendicular to grain are not common. It is suggested that in European standardisation either

– testing standard will be changed to be more directly relevant to structural use like ASTM D 143, or
– compression perpendicular to grain will be considered as serviceability limit state rather than ultimate limit state.

Shear test results show no correlation between strength and density, and suggest that same value should be used for all grades. We obtained 3.9 MPa for five percentile of spruce and 4.2 MPa for pine.

Traditionally 30MPa has been used in Finland as characteristic bending strength of round timber. The results here support this value to be used also for small diameter timber provided that there are visual grading limits for knots. Grading rules are suggested in Table 20. A special feature of small diameter round timber is that the ratio of compression strength parallel to grain to bending strength is lower than for sawn timber. This is obviously caused by larger effect of juvenile wood in compression than in bending.

The extensive research on moisture induced stresses perpendicular to grain suggests that we should not consider the lower load bearing capacity of curved beams as a material weakening effect. If doing so, there is no limit on how much weaker the material will become, because moisture gradients can and will cause splitting of wood without external loads. Therefore moisture gradients should be considered as external loads in a similar manor as snow, wind or thermal loads. Wood can be protected against these loads for example by surface coating.

Long term creep experiments are also reported in this publication. Under low load levels it takes about 20 years in heated or sheltered environment to reach a creep deformation which is 70% of elastic deformation.

Acknowledgements

While getting now retired, I want to thank VTT for having offered to me interesting working periods from 1970 to 1972, and from 1985 to 2007. Financial contributions of Tekes and European Commission have been crucial in execution of the work. Support of Finnish sawmilling and glulam industries is also gratefully acknowledged.

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Appendix A: Combigrade project material

Selection of test material (logs)

Five different sampling regions were chosen – three in Finland and two in North-Western Russia. The three areas in Finland were: Western Finland, Eastern Finland and Kainuu. The two in Russia were East Carelia and Vologda for spruce and Novgorod and Vologda for pine. All logs were gathered during winter 2005–2006 from six sawmills in Finland – also including the logs from the Russian sampling areas. The Russian logs were chosen from railway car loads or truck loads, whose origin was known with the accuracy of the province (“oblast”), which was enough for the purposes of this study. The sawmills and sampling areas are listed in Table A1. The logs were taken from the log supply of the sawmills so that not more than 5 logs were allowed from the same truck or the same railway car. In fact, the majority of the logs were gathered so that with high probability just one log was obtained from the same growth location (logging area). Logs were taken completely randomly: no quality assessment of logs was done at selection.

The sizes of the logs were chosen so that they corresponded to the normal sawing practise in the Nordic countries, which means that the log sizes used in this study for production of different sized sawn timber cross-sections were the same as are used in normal production of the same sizes. The number of selected logs per each dimension and per sampling area was 44, which was chosen so that a 10% surplus was taken compared to the targeted sample size 1000. Table A2 shows the log sizes and selected number of logs. The surplus was intended as a buffer against losses in transportation, etc.

Table A1. Sampling areas of logs. (*) Logs from coastal areas were not included.

SPRUCE			
Log labels	Region	Sawmill	Districts
KL	Western Finland	Kyröskoski sawmill	Tampere, Seinäjoki, Rauma(*
KE	Eastern Finland	Kitee sawmill	Kitee
KP	Kainuu	Soinlahti sawmill	Kajaani
KK	East Carelia	Kitee sawmill	
KV	Vologda	Kitee sawmill	
PINE			
Log labels	Area	Sawmill	Districts
ML	Western Finland	Merikarvia sawmill	Tampere, Seinäjoki, Rauma(*
ME	Eastern Finland	Kaukas sawmill	Lappeenranta, Mikkeli
MP	Kainuu	Kajaani sawmill	Kajaani
MN	Novgorod	Kaukas sawmill	
MV	Vologda	Kaukas sawmill	

Table A2. Log numbering system and mean top dimensions.

Sawn dimension	**Log numbers**	**Top diameter mm**	**Number of logs per area per species**	**Sawing pattern**
38 mm x 100 mm	1–44	176	44	2 ex log
50 mm x 100 mm	101–144	196	44	2 ex log
50 mm x 150 mm	201–244	230	44	2 ex log
44 mm x 200 mm	401–444	322	44	4 ex log
63 mm x 200 mm	301–344	290	44	2 ex log

Sawing and drying of test material

After the log-NDT measurements had been performed, the logs were sawn according to either the 2exlog pattern (most logs) or the 4exlog pattern (logs for the 44 x 200 dimension) into boards or planks corresponding to nominal dimension as shown in Table A2. The sawing patterns are illustrated in Figure A1. The sawing was made at Kymenlaakso Polytechnic at an educational sawing line, where the production speed was slow enough to allow the transfer of the log numbering onto the boards including an additional character that was added to the sawn pieces as illustrated in Figure A1. Basically, only one board out of each log was picked to be used as a test specimen in this study (either A or B by random as illustrated in Figure A1 for dimensions 38 x 100, 50 x 100, 50 x 150 and 63 x 200; for dimension 44 x 200 the logs were first divided into half by random and then from the first half either A or D was picked by random and from the other half either B or C by random). This way one piece was obtained for bending tests. The remaining boards were saved to be used as test material in other other tests.

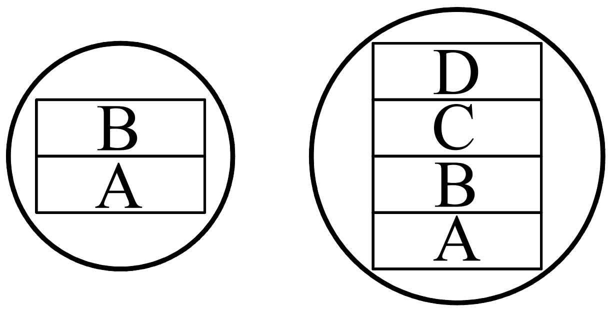

Figure A1. Sawing patterns of logs. Left – 2exlog used for dimensions 38 x 100, 50 x 100, 50 x 150, 63 x 200. Either the A-specimen or B-specimen was picked from each log for bending tests. Right – 4exlog used for 44 x 200. From half of the logs either the A-specimen or D-specimen was picked and from the other half either one B-specimen or C-specimen was picked for bending specimens.

The boards were dried also at Kymenlaakso polytechnic in a small kiln using a moderate drying schedule to avoid cracking. The target average final moisture content was 15%. Due to the limitation of kiln space available and the slow production speed of the sawing, a substantial amount of the boards had to be kept waiting for kilning outside. Due to this, the actually reached final average moisture content was lower, 11–12%. The boards were not planed after drying.

Series title, number and report code of publication

VTT Publications 668
VTT-PUBS-668

Author(s)
Ranta-Maunus, Alpo

Title
Strength of Finnish grown timber

Abstract
Strength and stiffness of timber have been studied in different projects during 1986–2007. This is a summary report of results which are considered relevant for European and international standardisation. It includes both new unpublished and already published information. The growth area of timber considered in this publication is primarily limited to Finland and parts of North Western Russia.

This experimental research concerns bending, tension, compression and shear strength and stiffness of sawn timber. It includes also tension perpendicular to grain of glulam and compression perpendicular to grain of sawn timber. Also, bending and compression strength of round timber is reported. In addition, long term creep results of glulam and other structural wood products are included in this publication.

ISBN
978-951-38-7067-6 (soft back ed.)
978-951-38-7068-3 (URL: http://www.vtt.fi/publications/index.jsp)

Series title and ISSN
VTT Publications
1235-0621 (soft back ed.)
1455-0849 (URL: http://www.vtt.fi/publications/index.jsp)

Project number

Date
December 2007

Language
English, Finnish abstr.

Pages
60 p. + app. 3 p.

Name of project
Combigrade

Commissioned by
Tekes, Wood Focus Ltd, Finnish glulam industry, Finnforest, Stora Enso, UPM, VTT

Keywords
timber, wood, spruce, pine, strength, bending, tension, compression, shear, creep, duration of load

Publisher
VTT Technical Research Centre of Finland
P.O. Box 1000, FI-02044 VTT, Finland
Phone internat. +358 20 722 4404
Fax +358 20 722 4374

Julkaisun sarja, numero ja raporttikoodi

VTT Publications 668
VTT-PUBS-668

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Nimeke

Suomalaisen puun lujuustutkimusten yhteenveto

Tiivistelmä

Julkaisu on yhteenveto puun lujuutta koskevista tutkimuksista VTT:ssa 1986–2007. Osa koetuloksista on ennen julkaisemattomia, osa on aikaisemmin julkaistuja. Julkaisu keskittyy sellaisiin tuloksiin, joilla on ilmeistä käyttöä puurakenteiden standardeja ja normeja kehitettäessä.

Tutkimus rajoittuu Suomessa ja lähialueilla kasvaneeseen kuuseen ja mäntyyn. Tuloksia verrataan myös julkaistuihin eurooppalaisiin tutkimustuloksiin. Julkaisu sisältää sahatavaran taivutus-, veto-, puristus ja leikkauslujuustuloksia ja liimapuun lujuustuloksia syysuuntaa vastaan kohtisuoran vetorasituksen alaisena sekä liimapuun virumistuloksia 16 vuotta kestäneen kuormituksen alaisena. Julkaisu sisältää myös pyöreän puun taivutus- ja puristus-koetuloksia.

ISBN
978-951-38-7067-6 (nid.)
978-951-38-7068-3 (URL: http://www.vtt.fi/publications/index.jsp)

Avainnimeke ja ISSN	Projektinumero
VTT Publications 1235-0621 (nid.) 1455-0849 (URL: http://www.vtt.fi/publications/index.jsp)	

Julkaisuaika	Kieli	Sivuja
Joulukuu 2007	Englanti, suom. tiiv.	60 s. + liitt. 3 s.

Projektin nimi	Toimeksiantaja(t)
Combigrade	Tekes, Wood Focus Ltd, Finnish glulam industry, Finnforest, Stora Enso, UPM, VTT

Avainsanat	Julkaisija
timber, wood, spruce, pine, strength, bending, tension, compression, shear, creep, duration of load	VTT PL 1000, 02044 VTT Puh. 020 722 4404 Faksi 020 722 4374

The publication reports strength testing results obtained during past 20 years by VTT and project partners. New and such older results are collected to this publication which are considered to be relevant for renewal of standards of structural timber. Main results were received in four research projects:

1) strength grading project in 1990's,
2) strength grading project 2003–2007 (Combigrade),
3) European project on the use of small diameter timber in construction in late 1990's and
4) European duration of load project in 1990's.

Julkaisu on saatavana

VTT
PL 1000
02044 VTT
Puh. 020 722 4520
http://www.vtt.fi

Publikationen distribueras av

VTT
PB 1000
02044 VTT
Tel. 020 722 4520
http://www.vtt.fi

This publication is available from

VTT
P.O. Box 1000
FI-02044 VTT, Finland
Phone internat. + 358 20 722 4520
http://www.vtt.fi

ISBN 978-951-38-7067-6 (soft back ed.)
ISSN 1235-0621 (soft back ed.)

ISBN 978-951-38-7068-3 (URL: http://www.vtt.fi/publications/index.jsp)
ISSN 1455-0849 (URL: http://www.vtt.fi/publications/index.jsp)