ESPOO 2008 VTT PUBLICATIONS 686

Antti Hanhijärvi & Alpo Ranta-Maunus

Development of strength grading of timber using combined measurement techniques

Report of the Combigrade-project – phase 2

VTT PUBLICATIONS 686

Development of strength grading of timber using combined measurement techniques

Report of the Combigrade-project – phase 2

Antti Hanhijärvi & Alpo Ranta-Maunus

ISBN 978-951-38-7106-2 (URL: http://www.vtt.fi/publications/index.jsp)
ISSN 1455-0849 (URL: http://www.vtt.fi/publications/index.jsp)

JULKAISIJA – UTGIVARE – PUBLISHER

VTT, Vuorimiehentie 3, PL 1000, 02044 VTT
puh. vaihde 020 722 111, faksi 020 722 4374

VTT, Bergsmansvägen 3, PB 1000, 02044 VTT
tel. växel 020 722 111, fax 020 722 4374

VTT Technical Research Centre of Finland, Vuorimiehentie 3, P.O. Box 1000, FI-02044 VTT, Finland
phone internat. +358 20 722 111, fax + 358 20 722 4374

VTT, Kemistintie 3, PL 1000, 02044 VTT
puh. vaihde 020 722 111, faksi 020 722 7007

VTT, Kemistvägen 3, PB 1000, 02044 VTT
tel. växel 020 722 111, fax 020 722 7007

VTT Technical Research Centre of Finland, Kemistintie 3, P.O. Box 1000, FI-02044 VTT, Finland
phone internat. +358 20 722 111, fax +358 20 722 7007

Technical editing Maini Manninen

Hanhijärvi, Antti & Ranta-Maunus, Alpo. Development of strength grading of timber using combined measurement techniques. Report of the Combigrade-project – phase 2. Espoo 2008. VTT Publications 686. 55 p.

Keywords strength grading, combined measurement techniques, sawn timber, bending strength, non destructive testing, X-ray scanning, frequency measurement, ultrasonic transit time, acoustic-ultrasonic measurement, destructive strength, stiffness, density

Abstract

More than 1000 pieces of spruce (*Picea abies*) logs and 1000 pieces of pine (*Pinus sylvestris*) logs were sampled mostly from Finland but also from North-Western Russia. Non-destructive measurements were first made on the logs and sawn timber of five different cross-section sizes were produced by sawing and kiln drying. Next, the sawn timber boards and planks went through several non-destructive measurements. NDT-measurements were made by 7 organisations producing some 50 different measured quantities of both logs and of each test piece. Finally, after all the non-destructive measurements, the test material was loaded to failure in bending, and grade determining properties (modulus of elasticity, bending strength and density) were measured. Degrees of determination were calculated between the non-destructively measured indicators and grade determining properties.

It could be concluded that the coefficients of determination – the r^2 values – between strength and most non-destructive indicators were remarkably higher for pine than for spruce. Especially, knot size and density are better grading parameters for pine than for spruce. This does not, however, indicate that yield to high grades would be in general better with pine than spruce, but it indicates that pine has larger variability of knot sizes and density, and consequently higher variability of strength. Log scanning can also produce strength indicators which are on the same level as some existing grading methods.

In parallel to this project another project that dealt primarily with grading of spruce based on tension strength was carried out and some results of that project are also reported.

Preface

This research has been carried out as the second part of “Combigrade” project. The objective of the work has been to experimentally compare existing and potential strength grading methods of sawn timber. The experimental work has been done during 2006.

The project was financed by Tekes – Finnish Funding Agency for Technology and Innovation, Wood Focus Finland and VTT. In addition, collaborating organisations have made important parts of the work on their own expense, which is briefly summarized as follows:

Logs were sampled with the help of Stora Enso Timber (Kitee Sawmill), UPM Kymmene (Kaukas Sawmill, Kajaani Sawmill) and Metsäliitto Co-operative (Soinlahti Sawmill, Kyröskoski Sawmill, Merikarvia Sawmill).

1. Bintec Oy made X-ray scanning of the logs.
2. Fibregen Instruments Limited made natural frequency measurements of the logs.
3. FinScan Oy made optical scanning of sawn boards.
4. CBS-CBT/Triomatic made ultrasonic measurements of boards in a glulam factory.
5. Microtec made X-ray and natural frequency measurements of boards in their laboratory.
6. Raute Timgrader Users Group made Raute Timgrader measurements at Sepa Oy in Keitele.
7. Brookhuis Micro Electronics / TNO Building and Construction Research made natural frequency measurements at a sawmill.
8. METLA (Finnish Foreset Research Institute) made the log selection and log manual measurements and helped in sawing the logs. It also made manual knot and other measurements of the boards in co-operation with VTT.
9. Beijing University of Forestry made the manual knot measurements and other measurements of the boards in co-operation with VTT and METLA.

Contribution of these organisations is gratefully acknowledged.

Project has been lead by a management team under the chairmanship of Vesa Pölhö (Stora Enso Timber). Other members of management team have been Jouko Silen (Stora Enso Timber), Ismo Heinonen (Vapo Timber), Risto Laaksonen and Jaakko Lehto (UPM-Kymmene), Aarni Metsä and Markku Lehtonen (Wood Focus), Timo Pöljö (Finnforest), Jaakko Riihinen (Fin Scan), Juha Vaajoensuu (Tekes), Laura Apilo, Heikki Kukko, Alpo Ranta-Maunus and Antti Hanhijärvi as secretary (VTT).

In parallel to Combigrade, a project that dealt with grading of spruce based on tension properties ("Combi-T"-project) was carried out co-operatively by Helsinki University of Technology (TKK) and VTT. The Combi-T-project obtained its test material from the same sampling procedure as this project and its results are mainly reported in (Poussa et al. 2007), but partly (correlations to NDT-parameters) included in this report.

Bending and tension strength values of Combigrade material are also separately and more comprehensively analysed and published as part of a summary report of strength of Finnish grown timber (Ranta-Maunus 2007).

Contents

List of symbols

C.o.V.	Coefficient of variation
E_{dyn}	Dynamic modulus of elasticity = dynamic MOE
E_{dyn}(Freq.)	Dynamic modulus of elasticity calculated based on natural frequency measurement and default density
E_{dyn}(Freq.&Dens.)	Dynamic modulus of elasticity calculated based on natural frequency measurement and density measurement
E_{dyn}(US)	Dynamic modulus of elasticity calculated based on velocity of ultrasound
E_{stat}	Static modulus of elasticity in NDT-measurement
I.P.	Indicating property
TKAR	Total Knot Area Ratio
MOE	Modulus of elasticity
MOR	Modulus of rupture = Longitudinal bending strength
NDT	Non-destructive testing
r	Correlation coefficient in linear regression analysis
r^2	Coefficient of determination in linear regression analysis
U.S.	Ultrasonic, Ultrasound
V	Coefficient of variation of measurement error

1. Introduction

1.1 Strength grading as part of the production process of sawn timber

Grading is an inseparable and important step in the modern production process of sawn timber. Through grading added value can be obtained for the timber products. Grading can be seen as the step in the production, in which the properties and the quality of the product are set, and these of course are important factors in determining its value on the market.

According to the purpose, grading of sawn timber can be categorized to either (1) appearance or (2) strength grading. Appearance grading is made to classify timber according to its aesthetic properties, so that aesthetically different pieces can be used in a place where they give most value. Strength grading – on the other hand – produces classified timber according to its mechanical properties, first and foremost strength.

Appearance grading has been – as measured by production volume – clearly more important than strength grading. This is natural, because most timber ends up either in a use where the outlook is important and mechanical strength has practically no relevance – or even if the strength is important, other factors determine the size to be so large that even a low strength is sufficient. This situation has caused the consequence that development of strength grading has not been very intensive in the past.

1.2 Purpose of strength grading

As opposite to appearance grading, strength grading has implications to the use of timber as load bearing structures in building construction. Therefore it also has implications to structural safety and it is regulated by the authorities. The purpose is to ensure that a particular piece of timber to be placed as a particular structural member in a building will have the capacity to carry (including safety margins) the load that is can be assumed to experience during the use (design load). To achieve a link between the properties of timber and the strength value that the designer can use in calculations, systems of strength classes have been adopted. In Europe, the requirements (~ minimum properties) of twelve strength classes of sawn softwood timber have been defined, they are denoted as: C14, C16, C18, C20, C22, C24, C27, C30, C35, C40, C45 and C50, where the character "C" refers to coniferous species and the number after it refers to the characteristic value of bending strength (in MPa) of timber pieces graded to that particular class (Table 1, see also ref. Glos 1995). The characteristic value (denoted with subscript *k*) means that 5% of the pieces graded in the class may have a lower strength value than indicated by the strength class characteristic value and at least 95% exceed it. To ensure that even the few pieces with strength below the characteristic value will not fail during service, an additional material safety factor is used, which is often 1.3 for structural timber, another safety factor is used to account for the uncertainty of loads. In addition to the requirement for the (1) bending strength, the European system of strength classes (EN 338, CEN 2003a) sets requirements for two other properties: (2) density (characteristic value) and (3) bending stiffness (mean value of modulus of elasticity [MOE]). The three properties of timber can be named as the *grade determining properties*. All other properties given in Table 1 are assumed to follow, if the three grade determining properties are shown to be satisfied by the graded timber.

Table 1. Strength classes and characteristic values according to EN338, coniferous species.

		C14	C16	C18	C20	C22	C24	C27	C30	C35	C40	C45	C50
in MPa													
Bending	$f_{m,k}$	14	16	18	20	22	24	27	30	35	40	45	50
Tension parallel	$f_{t,0,k}$	8	10	11	12	13	14	16	18	21	24	27	30
Tension perp	$f_{t,90,k}$	0,4	0,5	0,5	0,5	0,5	0,5	0,6	0,6	0,6	0,6	0,6	0,6
Compression	$f_{c,0,k}$	16	17	18	19	20	21	22	23	25	26	27	29
Compr. perp	$f_{c,90,k}$	2,0	2,2	2,2	2,3	2,4	2,5	2,6	2,7	2,8	2,9	3,1	3,2
Shear	$f_{v,k}$	1,7	1,8	2,0	2,2	2,4	2,5	2,8	3,0	3,4	3,8	3,8	3,8
in GPa													
Mean MOE	$E_{0,mean}$	7	8	9	9,5	10	11	11,5	12	13	14	15	16
5% MOE	$E_{0,05}$	4,7	5,4	6,0	6,4	6,7	7,4	7,7	8,0	8,7	9,4	10,0	10,7
Mean MOE perp	$E_{90,mean}$	0,23	0,27	0,30	0,32	0,33	0,37	0,38	0,40	0,43	0,47	0,50	0,53
Mean shear mod.	G_{mean}	0,44	0,5	0,56	0,59	0,63	0,69	0,72	0,75	0,81	0,88	0,94	1,00
in kg/m^3													
Density	ρ_k	290	310	320	330	340	350	370	380	400	420	440	460
Mean density	ρ_{mean}	350	370	380	390	410	420	450	460	480	500	520	550

NOTE: The tabulated properties are compatible with timber at a moisture content consistent with the temperature of 20^{0}C and relative humidity of 65%. Bending and tension parallel to grain strengths are given for timber width 150 mm, tension strength perpendicular to grain for reference volume 0,01 m^3.

1.3 Strength grading practices

To correctly determine the strength of a particular piece of timber, one has to break it, so it is no more useable as a load carrying component – true strength can only be determined in a destructive test. For strength grading purposes, it would actually not be necessary to test load the pieces to failure but only to the required value. Such a loading would knock off too weak pieces with 100% certainty, and such a method has been used in special cases.

In practice, almost all strength grading is based on indirect methods, where measurements or observations of other properties of timber pieces are used to predict the strength. The measurements are made by some suitable *non-destructive testing* (*NDT*) methods. Inevitably, indirect methods of predicting strength of individual pieces include uncertainty, since the capability of the method can never be perfect but contains measurement errors. The uncertainty has been dealt with in the strength grading system by setting *requirements to the statistical distribution of the grade determining properties* of timber pieces that fall into a certain strength class (EN 14081). The requirements for the statistical distribution of properties include minimum values for the characteristic value (bending strength, density) and mean value (bending MOE). Simply said, the whole development of strength grading system by the European system requires the demonstration that the required statistical properties can be met with sufficient confidence level by the method to be adopted.

The properties that are obtained by NDT-methods and used as predictors of grade determining properties are called *grade indicating properties* (I.P.'s). The effectiveness of a system depends on the prediction capability of the grade indicating properties and the accuracy by which they can be measured. Thus, the problem with stress grading focuses on these two key questions: (1) how to predict the strength of timber pieces by measuring other properties with the best possible reliability and (2) how to measure the predictor parameters with the best possible accuracy.

The challenges that are encountered in prediction of the strength of timber due to the variability of timber and the current state-of-the-art were extensively covered in the report of Phase 1 of this project (Hanhijärvi et al. 2005) and these will not be repeated here.

1.4 Motivation and purpose of this project

The Combigrade-project originated from the anticipation that the importance of strength grading of sawn timber will increase in the future. In Europe, the gradual application of the CE-marking of sawn timber for structural purposes requires that an increasing amount of timber will go through strength grading. On the other hand, much of the potential of Nordic timber is nowadays unused in what comes to strength. A large portion of the timber reaches much higher strength level than its present design strength value. With more accurate strength grading systems, this potential could be exploited.

The first goal of this project has been to examine different NDT-measurements and their combinations to find out which methods and which combinations of methods are the most effective in predicting strength and the other grade determining properties. When speaking of the "most effective" methods in this context, one should consider it from the economic point of view – not from strictly scientifically determined prediction accuracy. The economic effectiveness of a method is tied to the production: which method can give the best financial outcome for the company that uses it. And, that may be very different for different situations depending on the company and its operational environment, e.g. the product assortment, production volumes, raw material supply, markets, and so on – and of course the investment costs of the strength grading system itself.

The second goal has been to produce measurement data for the actual development of new machine strength grading methods to be adopted in practise. The development of strength grading machines is expensive, and one of the most expensive tasks is the destructive testing of sufficiently high number of pieces in order to determine settings for the method and to show that the statistical requirements the distribution of grade determining properties are met by the method. EN 14081 requires the testing of at least 900 specimens for the acceptance of a new strength grading machine by the so called machine control method.

To facilitate the development of new strength grading methods and machines and their adoption in the real life, the philosophy adopted in the Combigrade-project was that, if the same (expensive) destructive data can be used for the development of several method by many users, it will be less expensive per machine and then make easier the development of new machines. Following this idea, the project work was arranged so that grading machine producers were invited to participate in the project as partners and make their own NDT-measurements at their own cost and hand the results over for the project to use in scientific work. On return, the partners could receive the destructive results produced by the project for use in their own product development work.

In parallel to Combigrade, a project called "Combi-T" (T standing for tension) was carried out co-operatively by Helsinki University of Technology (TKK) and VTT to study the strength grading of timber based on tension properties (tension strength and tension MOE). The Combi-T-project obtained its test material from the same sampling procedure as this project and its results are mainly reported in (Poussa et al. 2007), but some results – in particular, correlations to NDT-parameters – included in this report.

1.5 Contents of the project

The project was carried out in two phases:

> Phase 1 was a feasibility study, in which a small sample was used – appr. 100 spruce specimens and appr. 100 pine specimens. Phase 1 and its results have been reported in (Hanhijärvi et al. 2005).
>
> Phase 2 was a large study with a very large sample size – more than 1000 spruce specimens and more than 1000 pine specimens. Phase 2 is the subject matter of this report.

1.6 Regression analysis as a source of prediction model

The strength of timber can be predicted by the measurement or quantification of properties that have a clear effect on strength, or, on those measurable properties that do not directly affect strength but are good indicators of it. For example, knots are known to be one of the key factors that define strength. Stiffness (modulus of elasticity, MOE), on the other hand, is not a direct factor to define strength, but because it is dependent on the same factors that define strength, is a good indicator of strength. Both types of properties can be considered as predictors of strength. In strength grading of structural timber the greatest emphasis should naturally be put on those non-destructively measurable parameters (predictors) that have the greatest ability to predict strength.

The basis of strength grading with non-destructive measurements is the existence of a relation between the strength and one or more predictor parameters. The relation must be described mathematically. The exact (deterministic) relation cannot be formulated due to its complexity, but it can be established from empirical observations (results of experiments) using mathematical statistical methods, usually regression analysis. It should be noted that statistical methods are not the only possible way to develop a strength grading system: basically any method that can be shown to produce a sample whose characteristic value is above the required value is sufficient.

In the analyses of this work, different NDT-methods are evaluated by regression, and, in all cases only simple linear regression analysis is adopted. The regression analysis yields among other results the so called '*coefficient of correlation*', r. Its square is called '*coefficient of determination*', r^2. The value of r^2 indicates the portion of the total variation of the predicted variable which is explained by the predictor. E.g., if $r^2 = 1$, the predictor can explain the variation perfectly, if $r^2 = 0.5$ it can explain half of it, if $r^2 = 0$, it cannot explain anything about the variation. In this work, the coefficient of determination is used solely as a measure of the ability of a method to predict the grade determining properties.

It is not possible to go into details about the regression analysis procedure itself, but it should be noted that there are two important things that should be taken into account when using it:

- If the variation of the predictor properties (indicating parameters) in the experimental data is small, it is meaningless to carry out a regression analysis.
- The result of a regression analysis should not be used for prediction with values of the indicating parameter that are outside the variation range of it in the experimental data set, on which the regression analysis was based. In other words, one has to be very careful with extrapolation.

2. Material

2.1 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 Karelia 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. However, sampling in "East Karelia" does not correspond to an administrative area but rather to an area around Lake Ladoga. The sawmills and sampling areas are listed in Table 2 and also illustrated in Figure 1 and Figure 2. 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 log dimensions were measured by METLA and the average, minimum and maximum top diameter dimensions of logs in each area are given in Table 4 and Table 5. 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 3 shows the log sizes and selected number of logs. The surplus was intended as a buffer against losses in transportation, etc.

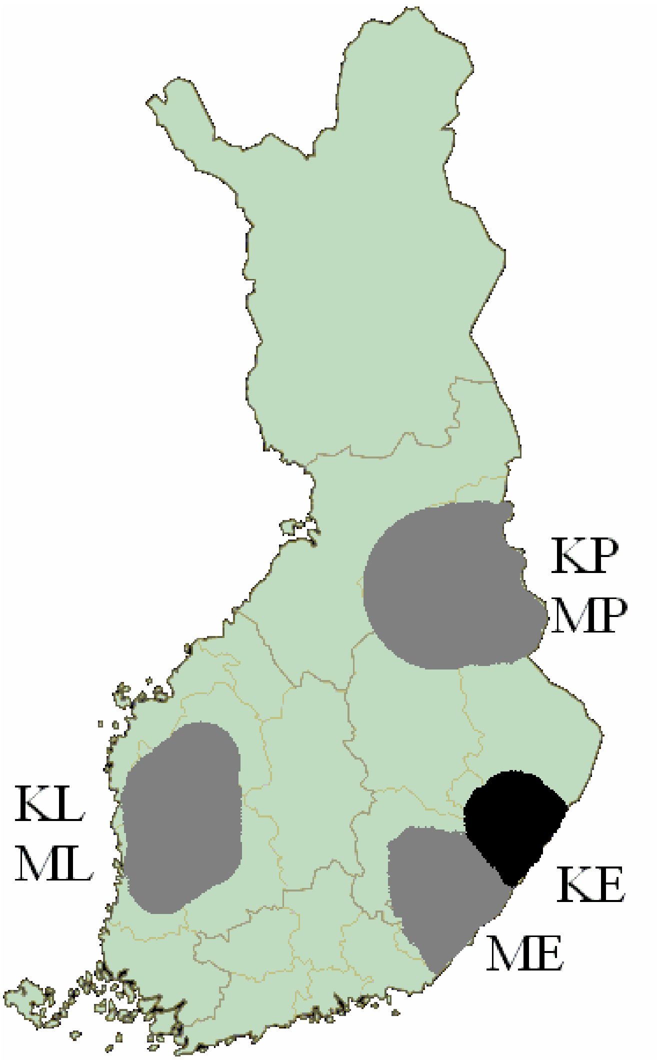

Figure 1. Sampling areas in Finland. (Also KE and ME overlap.)

Figure 2. Sampling areas in Russia. Note that "East Karelia" shown here does not correspond to any administrative area.

Table 2. Sampling areas of logs. (*) Logs from coastal areas were not included. "East Karelia" does not correspond to any administrative area.

SPRUCE (Label K)			
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 Karelia"	Kitee Sawmill	
KV	Vologda	Kitee Sawmill	
PINE (Label M)			
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 3. Log numbering system and sawing pattern.

LOG SERIES	Sawn dimension	Log numbers	Target number of logs per area per species	Sawing pattern
0-series	38 mm x 100 mm	1–44	44	2 ex log
100-series	50 mm x 100 mm	101–144	44	2 ex log
200-series	50 mm x 150 mm	201–244	44	2 ex log
400-series	44 mm x 200 mm	401–444	44	4 ex log
300-series	63 mm x 200 mm	301–344	44	2 ex log

Table 4. Measured top diameters in (mm) of collected spruce logs.

SERIES	AVERAGE	MIN	MAX
0-series	182	154	244
KE	170	154	183
KK	214	182	244
KL	170	156	183
KP	171	163	184
KV	185	161	227
100-series	204	173	274
KE	186	173	212
KK	249	190	274
KL	188	179	201
KP	186	178	197
KV	201	184	248
200 series	234	206	298
KE	233	206	298
KK	263	226	289
KL	220	208	233
KP	219	207	237
KV	227	206	270
300 series	292	219	347
KE	290	275	318
KK	293	275	347
KL	301	285	320
KP	286	275	297
KV	288	219	340
400 series	323	292	398
KE	316	296	351
KK	330	303	398
KL	326	314	342
KP	317	301	345
KV	323	292	355

Table 5. Measured top diameters in (mm) of collected pine logs.

SERIES	AVERAGE	MIN	MAX
0-series	171	152	232
ME	158	152	171
ML	164	155	176
MN	182	154	232
MP	168	159	179
MV	183	159	223
100-series	189	163	221
ME	173	163	214
ML	185	173	202
MN	195	182	207
MP	193	177	212
MV	199	173	221
200-series	225	204	282
ME	209	204	235
ML	222	211	239
MN	227	208	243
MP	227	218	238
MV	240	213	282
300-series	288	264	321
ME	275	264	298
ML	290	274	305
MN	295	272	314
MP	288	270	311
MV	292	274	321
400-series	322	296	364
ME	305	296	317
ML	343	320	364
MN	319	298	347
MP	320	306	335
MV	321	303	353

2.2 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 44x200 dimension) into boards or planks corresponding to nominal dimension as shown in Table 3. The sawing patterns are illustrated in Figure 3. 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 3. Basically, only one board out of each log was picked to be used as a test specimen in this study. This was done by picking either A or B by random for dimensions 38x100, 50x100, 50x150 and 63x100; for dimension 44x200 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 per every log was obtained for this study.

From the remaining boards, test material was chosen for the parallel project that studied grading based on tension properties (Combi-T-project, reported in Poussa et al. 2007). Since the number of specimens in the Combi-T-project was approximately 1/2 of that in Combigrade-project, specimens were chosen by taking randomly half of the remaining pieces of dimensions 38x100, 50x100 and 50x150 as well as half of those pieces of dimension 44x200 that had been sawn symmetrically compared to the specimen taken for Combigrade. (I.e. if A [resp. D] had been chosen for Combigrade, only the remaining D [resp. A] was considered possible for Combi-T. Similarly, if B [resp. C] had been chosen for Combigrade, only the remaining C [resp. B] was considered possible for Combi-T.) The largest dimension 63x200 was not included in the study of tension properties.

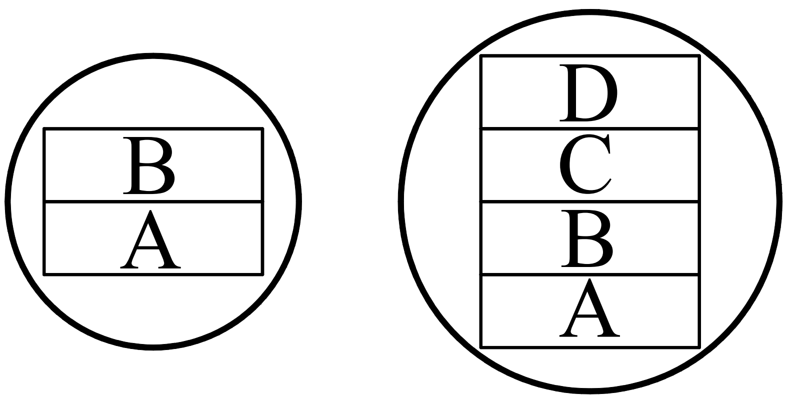

Figure 3. Sawing patterns of logs. Left – 2exlog used for dimensions 38x100, 50x100, 50x150, 63x200. Either the A-specimen or B-specimen was picked from each log for this study. Right – 4exlog used for 44x200. From half of the logs either the A-specimen or D-specimen was picked and from the other half either the B-specimen or C-specimen was picked.

The boards were also dried 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.

3. Methods

3.1 Basic method of study

As described above in the Introduction, the objective of the work was to study how well different NDT-methods and their combinations can predict the three grade determining properties of EN 14081: bending strength, bending stiffness and density. The idea was to first make the various NDT-measurements on the test material, and then make destructive tests to determine the grade determining parameters of each board and finally analyse and evaluate the NDT-data, compare it to the destructive data.

Strength grading equipment manufacturers were invited to participate as partners in the project and to perform measurements by their own equipment and provide the data for use in the project. A list of participating companies or institutes along with the used techniques is given below in Table 6. The Combigrade project itself together with some related projects arranged the employment of few techniques which were considered interesting but were not covered by any measurements by the participating partners. These measurements were carried out mainly as co-operation between VTT and METLA (Finnish Forest Research Institute).

Table 6. Partners and measurement methods in Combigrade-2.

Partner	Method (auxiliary measurements in brackets)	Measured property
Log measurements		
Bintec	Log-Xray	Density Knot parameters Annual ring width
Fibregen	Log-Frequency	Natural frequency (longitudinal)
VTT+METLA (Combigr. and related projects)	Log weight Log-Frequency Ultrasonic	Mass of logs Natural frequency (longitudinal) Transit time of ultrasound
Board measurements		
FinScan Oy	Visual scanning of board sides	Knot parameters
CBS-CBT/ Triomatic	Ultrasound Hardness (Electric resistance)	Transit time Density (Moisture content)
Microtec/ GoldenEye+Viscan	Frequency Weight X-ray	Natural frequency (longitudinal) Mass of board Density, knot parameters
Raute Users' Group/Raute Timgrader	Flatwise static bending	Flatwise bending modulus of elasticity
Brookhuis Micro Electronics/TNO	Frequency Weight	Natural frequency (longitudinal) Mass of boards
VTT+METLA (Combigr. and related projects)	Weight Manual Knot meas.	Weight of boards Knot characteristics

3.2 NDT-measurement techniques

In the following, a brief description is given about how each non-destructive measurement was used in the project.

3.2.1 X-ray scanning of logs

The X-ray scanning of the logs was carried out with a machine by Bintec Oy. The equipment is running at a sawmill and can be used for quality grading of logs. The scan is performed by irradiating logs from several sides while they move past the machine. The intensity of the transmitted radiation is measured on the opposite side of the irradiators. By the method, a three dimensional picture of the log and its interior can be obtained and different parameters concerning the log calculated. These parameters include various density parameters, knot parameters and ring width parameters.

3.2.2 Frequency measurement of logs

The natural frequency of the logs was measured by Fibregen using the Director HM200 apparatus. This method measures the natural frequency of the log caused by the longitudinal vibration and calculate the velocity of the sound in the log. The measurement itself is carried out by placing a vibration sensor on the log end and hitting the log with a hammer to excite the vibration. The measurement was made outside at a sawmill yard. While measuring the logs were in piles. Based on the measured natural frequency and an additional length measurement and assuming a default density value, the dynamic modulus of elasticity of the log can be calculated.

3.2.3 Ultrasonic transit time of logs

The ultrasound transit time of the logs was measured by VTT and METLA using the Sylvatest apparatus by CBT S.A. This method measures the time in which the sound travels through the log longitudinally. The measurement is performed by attaching a starter and receiver transducer on the ends of the log. In this project, the measurements were performed just before the sawing, and the logs were in the outside temperature. Based on the transit time measurement and length measurement a dynamic modulus of elasticity (assuming a default density value) can be calculated, but it should be noticed that this dynamic MOE is based on a different physical phenomenon than the one obtained by the natural frequency measurement.

3.2.4 Visual scan of board sides

Visual scan of board sides was performed by FinScan Oy at a sawmill. The scan produces digital images of the board sides and edges, which can be analysed by image analysis techniques to obtain various parameters (e.g. knots).

3.2.5 Natural frequency measurement of boards (2)

The measurement of natural frequency of boards was made separately by two partners: Microtec S.r.l. and Brookhuis Micro-Electronics BV / TNO Building and Construction Research. Both measurements registered the natural frequency in longitudinal vibration and were carried out in laboratory. The measurement itself occurs by placing the board on two elastic supports and hitting one end of it by a hammer, or something similar, which excites the vibration. The frequency can be measured in several different ways (microphone, accelerometer, optically). Obviously, the measurement technique does not affect the frequency itself but can have an effect on the robustness of the method. Based on the natural frequency and length measurement and assuming a default value of density, a dynamic MOE can be calculated. If a measured density is used instead of a default density, a more accurate dynamic MOE value is obtained. Obviously the prediction capability of the one including information about density is higher than the one without it. Here the two are denoted as E_{dyn}(freq.) and E_{dyn}(freq. & dens.). Microtec's measurements were made in laboratory conditions, TNO's measurements in outside but sheltered conditions.

3.2.6 X-ray scanning of boards

Microtec S.r.l. performed X-ray scanning of the boards using the Golden Eye strength grading machine (Giudiceandrea 2005). The board is fed through the machine and is irradiated from the other side. The transmitted intensity is recorded from the other side and a picture of the board and its interior is obtained. The measurement was made in laboratory. Various parameters concerning the board can be calculated including density and knot parameters.

3.2.7 Acoustic-ultrasonic measurement of boards

The acoustic-ultrasonic measurement was performed by CBS-CBT using the Triomatic strength grading machine (Sandoz 1989, 1996). The measurement functions by attaching two probes on the ends of the board. An ultrasonic sound pulse is excited to the board at one end. At the other end the transit time and transmitted energy is measured. As an auxiliary measurement, the moisture content was measured by the electric resistance method. Along with the moisture content measurement, density is evaluated bases on the hardness of the board. The measurements were made at a glulam factory. From the results the mechanical properties of the board can be predicted.

3.2.8 Density measurement by scale

The global density of the boards was measured by weighing and measuring the length of the specimens in laboratory by VTT, METLA and BUF. For determination of the volume the nominal board width and thickness were used.

3.2.9 Flatwise bending stiffness (Raute Timgrader)

The Finnish Raute Timgrader Users' Group arranged the measurements with Raute Timgrader strength grading machine in industrial conditions. The machine functions by measuring the necessary force that is needed to effect a certain deflection in flatwise bending, i.e. stiffness. The boards are fed through the machine and the stiffness is output at approx. 10 cm intervals.

3.2.10 Manual knot measurements

The manual knot measurement was made in conjunction with the destructive tests: before the testing the knot geometry of the most highly loaded area was recorded. Based on the records, the total knot area ratio (TKAR) was determined for the boards. Also other defects were recorded including top defects, bark, wane, etc.

3.3 Destructive tests

The bending strength, bending stiffness and density were determined by destructive tests according to EN 408 in four-point bending. The bending stiffness was measured by two ways: "locally" based on the deflection of the constant moment region between the presses and "globally" based on the deflection of the whole span. The corresponding modulus of elasticity (MOE) values were denoted by "MOE-local" and "MOE-global". The density was measured on small slices cut from the neighbourhood of the failure location. The density was determined both at the testing condition at approx. 12% moisture content (R_u) and at absolute dry conditions (R_0). Simultaneously, the moisture content was determined from the slices. The testing details are shown in Table 7. All specimens were allowed to obtain equilibrium moisture content at 20°C and 65% RH before testing.

Table 7. Destructive test arrangement details.

Cross-sections	38x100 50x100	50x150	44x200 63x200
Nominal board height, h, mm	100	150	200
Nominal board width, b, mm	38, 50	50	44, 63
Total span, mm	1800	2700	3600
Distance between presses, mm	600	900	1200
Span of defl. meas. for MOE-local, mm	500	750	1000

The positioning of each board to the test rig was determined so that the weakest point would be located between the presses (i.e. at constant moment region, the most highly loaded region), if possible. The presumed weakest point was determined based on manual visual inspection. The choice of the edge to be under tension stress was made at random.

4. Results and analysis

4.1 Destructive strength, stiffness and density test results and their correlations

A statistical summary of the destructive test results is shown in Table 8 and Table 9 for spruce and pine, respectively. The results are grouped according to the cross-section size. In Table 10 the results are grouped according to the growth region. Table 11 contains the statistical summary of the tension test results of the Combi-T-project.

Table 8. Statistical summary of the destructive bending test results of spruce, means and coefficients of variation. All C.o.V's are given in per cent. Moisture content MC as % (dry basis).

SPRUCE BEND.	N	MC, % C.o.V	R_u, kg/m^3 C.o.V	R_0, kg/m^3 C.o.V	MOE-Glob MPa C.o.V	MOE-Loc MPa C.o.V	MOR MPa C.o.V
38x100	201	11.8	437	390	10900	11600	45.6
		4.0	10.0	9.9	16.9	18.4	22.2
50x100	211	12.5	442	393	11100	12300	48.2
		3.5	9.0	8.9	15.1	15.5	20.8
50x150	214	12.4	443	394	11200	12400	46.3
		4.0	10.5	10.3	15.8	17.2	24.8
44x200	139	12.1	428	382	10200	11300	35.6
		4.4	9.0	8.8	17.8	19.8	31.7
63x200	156	13.0	434	384	11000	12200	41.3
		7.6	9.2	9.1	14.7	15.9	24.1
All	921	12.3	438	390	10900	12000	44.1

Table 9. Statistical summary of the destructive bending test results of pine, means and coefficients of variation. All C.o.V's are given in per cent. Moisture content MC as % (dry basis).

PINE BEND:		MC	R_u	R_0	MOE-Glob	MOE-Loc	MOR
38x100	205	11.6	458	407	10100	10900	41.1
		5.4	10.4	12.7	19.3	20.7	30.9
50x100	211	11.9	456	407	9800	10500	40.6
		3.7	11.2	11.1	21.4	23.5	34.8
50x150	194	11.7	461	412	10200	11100	39.5
		4.4	10.6	10.3	19.5	20.6	33.0
44x200	141	11.7	496	444	10600	11600	36.8
		5.6	13.3	13.1	22.2	22.7	38.4
63x200	183	12.5	483	429	10600	11700	39.8
		5.3	13.5	13.5	20.1	21.1	33.2
All	934	11.9	468	418	10200	11100	39.7

Table 10. The average values of destructive results as calculated according to the growth area.

SPRUCE	West-Finland	Kainuu	East-Finland	East Karelia	Vologda
Ru	441	457	437	420	436
MOE-Glob	11205	11218	10737	10330	11189
MOR	44.3	47.0	42.4	41.9	45.3
PINE	**West-Finland**	**Kainuu**	**East-Finland**	**Novgorod**	**Vologda**
Density	492	495	481	440	435
MOE-Glob	10775	11159	10801	9212	9212
MOR	43.8	46.6	42.8	31.8	33.9

Table 11. Statistical summary of the destructive tension test results of spruce (Combi-T-project), means and coefficients of variation. All C.o.V's are given in per cent. Moisture content MC as % (dry basis).

SPRUCE TENSION	**N**	**MC, % C.o.V**	**Ru, kg/m^3 C.o.V**	**MOE MPa C.o.V**	**Strength MPa C.o.V**
38x100	115	12.0	434	11900	34.6
		4.7	10.8	16.3	30.7
50x100	113	12.7	446	12000	35.1
		3.5	10.2	15.8	26.0
50x150	115	12.5	441	12000	34.7
		3.3	9.6	16.0	27.7
44x200	114	12.3	423	11200	29.8
		3.7	9.6	20.3	37.4
All	457	12.4	436	11800	31

4.2 Correlations between strength, stiffness and density

The correlations between the properties obtained in the destructive tests are shown in Table 12 and Table 13 in terms of the coefficient of determination r^2. It can be noticed that the two densities, R_u and R_0, show practically perfect correlation and that the use of only one is sufficient.

Similar correlations between the properties obtained in the destructive tests of the parallel project Combi-T are shown in Table 14.

Table 12. Degree of determination r^2 (per cent) of correlations between the results of destructive tests for spruce.

BENDING					
SPRUCE 38x100	MOR	MOE_Glob	MOE_Loc	Ru	R0
MOR	100	65	62	31	31
MOE_Glob	65	100	89	54	53
MOE_Loc	62	89	100	42	42
Ru	31	54	42	100	100
R0	31	53	42	100	100
SPRUCE 50x100	MOR	MOE_Glob	MOE_Loc	Ru	R0
MOR	100	67	64	31	31
MOE_Glob	67	100	91	55	55
MOE_Loc	64	91	100	49	49
Ru	31	55	49	100	100
R0	31	55	49	100	100
SPRUCE 50x150	MOR	MOE_Glob	MOE_Loc	Ru	R0
MOR	100	67	64	29	28
MOE_Glob	67	100	95	60	59
MOE_Loc	64	95	100	59	58
Ru	29	60	59	100	100
R0	28	59	58	100	100
SPRUCE 44x200	MOR	MOE_Glob	MOE_Loc	Ru	R0
MOR	100	66	56	23	22
MOE_Glob	66	100	88	37	36
MOE_Loc	56	88	100	37	36
Ru	23	37	37	100	100
R0	22	36	36	100	100
SPRUCE 63x200	MOR	MOE_Glob	MOE_Loc	Ru	R0
MOR	100	55	47	14	15
MOE_Glob	55	100	92	41	40
MOE_Loc	47	92	100	36	36
Ru	14	41	36	100	99
R0	15	40	36	99	100

Table 13. Degree of determination r^2 (per cent) of correlations between the results of destructive tests for pine.

BENDING					
PINE 38x100	MOR	MOE_Glob	MOE_Loc	Ru	R0
MOR	100	75	64	56	55
MOE_Glob	75	100	90	66	65
MOE_Loc	64	90	100	60	60
Ru	56	66	60	100	98
R0	55	65	60	98	100
PINE 50x100	MOR	MOE_Glob	MOE_Loc	Ru	R0
MOR	100	79	76	53	53
MOE_Glob	79	100	93	63	63
MOE_Loc	76	93	100	60	61
Ru	53	63	60	100	100
R0	53	63	61	100	100
PINE 50x150	MOR	MOE_Glob	MOE_Loc	Ru	R0
MOR	100	72	67	51	51
MOE_Glob	72	100	91	64	64
MOE_Loc	67	91	100	61	61
Ru	51	64	61	100	100
R0	51	64	61	100	100
PINE 44x200	MOR	MOE_Glob	MOE_Loc	Ru	R0
MOR	100	72	67	44	44
MOE_Glob	72	100	94	58	58
MOE_Loc	67	94	100	54	54
Ru	44	58	54	100	100
R0	44	58	54	100	100
PINE 63x200	MOR	MOE_Glob	MOE_Loc	Ru	R0
MOR	100	73	67	43	42
MOE_Glob	73	100	96	49	48
MOE_Loc	67	96	100	49	48
Ru	43	49	49	100	100
R0	42	48	48	100	100

Table 14. Degree of determination r^2 (per cent) of correlations between the results of destructive tests for spruce in tension.

TENSION			
SPRUCE 38x100	Strength	MOE-tens	Ru
Tension Strength	100	53	30
MOE – Tension	53	100	53
Ru	30	53	100
SPRUCE 50x100	Strength	MOE_tens	Ru
Tension Strength	100	52	17
MOE – Tension	52	100	52
Ru	17	52	100
SPRUCE 50x150	Strength	MOE_tens	Ru
Tension Strength	100	65	33
MOE – Tension	65	100	62
Ru	33	62	100
SPRUCE 44x200	Strength	MOE_tens	Ru
Tension Strength	100	56	28
MOE – Tension	56	100	61
Ru	28	61	100

4.3 Correlations between destructive results and individual NDT-results

As a basic treatment for the gathered NDT-data, correlation analyses between the individual NDT-parameters and the destructively measured properties were carried out. In this way, the coefficient of determination r^2 of each measured property in linear regression as a predictor for the destructively determined properties was obtained. Table 15 contains specific information on the exact parameters used and how the analysis was made for the different measurements.

Table 16 and Table 17 list the r^2-values for each parameter for spruce and pine, respectively. The indicating properties obtained from the strength grading machines used are included as single parameters, even if some of them require more than one measurement.

As a next step, some multi-variable regression analyses with two or more NDT-parameters as simultaneous predictors of the destructively determined properties were carried out. In Combigrade-1 this kind of analyses was made quite comprehensively, including combinations which are quite unlikely to be realised in practice. Because not very many measurements and parameters combinations are really relevant for combination measurements, only selected practical ones were included here. These combination analyses were made with same parameter data as the single parameter regression analyses. The results of the combination analyses are included in Table 16 and Table 17, as well as in Table 18 for tension results, in combination with the results of the analyses of the single parameters.

Table 15. Details about the parameters used in analysis of correlations.

Partner/ Method	Analysis of raw measurement data	Parameters used in correlation analysis	Notes about correlation analysis
Bintec Oy/ Log-Xray	by partner	Density (heart and sap) Knot parameters Annual ring width	
Fibregen/ Log Frequency	by partner	Dynamic MOE (Freq)	
VTT+METLA/ Log Acoustic Log Density	by VTT	Dynamic MOE (US) Log Mass, volume	
CBS-CBT/ Ultrasound	by partner	US-velocity, US-peak, density Indicating property	
Microtec/Natural Frequency Density	by partner	Dynamic MOE (Freq) Dynamic MOE (Freq.+dens.), I.P.	
Microtec/ X-ray	by partner	Density parameters (Aver., Clear, Min.) Knot parameters, I.P.	Maximum knot values at the constant moment region
Brookhuis/TNO/ Natural Frequency Density	by partner	Frequency Edyn (Freq+dens) I. P.	
Raute Users Group/Flatwise static bending	by VTT	Flatwise bending MOE (I.P.)	Destructive test loading position information used in analysis
VTT+METLA	by VTT	Global density by weighing	No moisture correction was applied
VTT+METLA	by VTT	Total Knot Area Ratio (TKAR)	Maximum value at the constant moment region

Table 16. Coefficient of determination r^2 of individual NDT-measurements or combined ones (grading machine IP's) to destructively determined properties in bending for spruce. NDT-measurement type codes: L = length, W = weighing, F = natural frequency, X = X-ray (X_D = Xray with only density used), U = Ultrasonic, R = Electric Resistance (for moisture content), B = Bending stiffness, V = Dimensions (Length and Volume), I = Visual inspection.

BENDING		destruct. r^2 of / to:	Strength, MOR						Stiffness, MOE-Glob.						Density; Ru					
SPRUCE Source	Meas. incl.	Size	ALL	38x100	50x100	50x150	44x200	63x200	ALL	38x100	50x100	50x150	44x200	63x200	ALL	38x100	50x100	50x150	44x200	63x200
Destructive		MOR	100	100	100	100	100	100	62	65	67	67	66	55	26	31	31	29	23	14
Destructive		MOE-Global	62	65	67	67	66	55	100	100	100	100	100	100	51	54	55	60	37	41
Destructive		Dens, Ru	26	31	31	29	23	14	51	54	55	60	37	41	100	100	100	100	100	100
Bintec/Log X-ray	X	Log-X knot A	8	16	15	34	18	15	11	12	5	30	20	14	1	0	0	11	5	1
Bintec/Log X-ray	X	Log-X knot B	17	13	16	12	8	13	10	10	9	10	9	9	3	1	2	9	0	1
Bintec/Log X-ray	X	Log-X knot C	11	26	18	28	16	13	11	18	4	23	17	10	3	3	1	13	5	3
Bintec/Log X-ray	X	Log-X density sapw.	0	0	0	0	0	0	2	1	1	2	2	3	6	7	6	2	15	4
Bintec/Log X-ray	X	Log-X density heartw	11	4	6	9	8	11	17	11	16	18	15	23	41	39	44	38	44	53
Bintec/Log X-ray	X	Log-X annual ring	11	8	8	19	3	7	7	9	7	11	4	4	2	3	2	5	0	2
Bintec/Log X-ray	X	Log-X all	45	41	42	53	29	35	43	45	44	54	40	47	55	60	61	56	49	65
Fibregen/Log-Freq.	F,L	Log-Edyn (Freq.)	16	14	24	13	31	9	28	15	26	31	47	35	7	1	8	14	12	10
VTT+METLA/Log-Den.	W,V	Log-Dens	0	0	0	0	2	1	2	1	3	0	4	3	6	8	8	1	12	4
VTT+METLA/Log-	F,L	Log-Edyn(Freq.)	15	15	25	20	27	13	24	26	38	32	60	37	8	2	11	18	15	17
VTT+METLA/Log-Edy.	F,W,V	Log-Edyn	16	14	14	23	23	15	29	32	35	44	49	46	19	16	24	27	31	27
VTT+METLA/Log-US	U,L	Log-US	19	22	22	27	22	16	35	33	32	42	51	42	14	5	11	27	15	17
VTT+METLA/Log-Edy.	U,W,V	Log-Edyn(US+dens)	21	18	17	27	24	18	43	38	39	54	53	51	29	24	30	39	34	28
Raute/flatwise stiffn.	B	Raute Estat (flatwise)	(54)	55	54	60	57	45	(75)	83	78	77	79	59	(54)	62	62	62	42	42

BENDING		destruct. r^2 of / to:	Strength, MOR						Stiffness, MOE-Glob.						Density; Ru					
SPRUCE Source	Meas. incl.	Size	ALL	38x100	50x100	50x150	44x200	63x200	ALL	38x100	50x100	50x150	44x200	63x200	ALL	38x100	50x100	50x150	44x200	63x200
CBS-CBT/Ultrasonic	U,R,L	US-speed	45	41	48	51	44	44	54	53	57	59	65	52	14	11	21	21	13	8
CBS-CBT/Ultrasonic	U,R,L	US-peak	4	1	2	1	2	2	0	0	2	0	1	0	1	0	0	0	0	0
CBS-CBT/Ultrasonic	R,L	Dens. (Hardness)	11	11	10	8	11	8	18	20	23	14	20	16	36	43	38	28	48	30
CBS-CBT/Ultrasonic	U,R,L	I.P.	49	46	48	51	46	45	63	64	65	62	73	60	43	48	46	38	51	34
MiCROTEC/Freq.	F,L	Edyn1(Freq)	48	45	48	58	50	44	65	62	60	68	73	64	13	11	15	21	8	8
MiCROTEC/Freq.+den	F,X_D,L	Edyn1(Freq.+dens.)	57	56	57	60	58	48	88	88	86	90	91	87	62	68	70	70	44	49
MiCROTEC/X-ray	X_D	X-ray aver density	28	28	27	32	25	15	52	51	51	62	44	45	90	94	94	91	85	86
MiCROTEC/X-ray	X_D	X-ray min density	33	32	32	39	30	20	59	57	58	68	50	52	89	94	92	90	83	85
MiCROTEC/X-ray	X_D	X-ray clear density	32	31	31	36	31	18	57	55	56	65	51	49	91	95	95	91	84	86
MiCROTEC/X-ray	X	X-ray knot a	38	48	34	49	45	30	35	42	27	41	42	22	15	14	18	23	8	7
MiCROTEC/X-ray	X	X-ray knot b	40	43	38	52	46	30	36	36	29	45	43	21	12	9	15	21	8	4
MiCROTEC/X-ray	X	X-ray knot c	42	50	36	54	42	30	34	38	25	45	36	18	11	11	13	21	5	3
MiCROTEC/X-ray	X	X-ray knot d	39	36	34	45	41	34	32	31	24	38	37	20	10	6	14	17	8	2
MiCROTEC/X-ray	X	X-ray I.P.	53	59	50	60	58	40	70	72	64	77	69	59	91	95	95	92	84	86
MiCROTEC/Freq.+X-r	F,X,L	Edyn1 + X-ray I.P.	64	64	66	69	66	55	89	89	87	91	92	87	91	95	95	92	84	86
TNO/Brookhuis	F,L	Edyn2 (Freq.)	44	41	42	55	43	40	60	56	56	66	69	60	12	10	12	18	8	7
TNO/Brookhuis	W,L	Global density	26	26	25	31	26	16	50	49	48	59	42	45	88	93	92	88	81	83
TNO/Brookhuis	F,W,L	Edyn2(Fr+D.)-IP MOE	53	55	55	60	54	47	87	88	85	89	88	88	60	66	68	67	44	49
TNO/Brookhuis	F,W,L	Edyn2(Fr+D.)-IP MOR	42	49	48	53	51	40	79	82	79	84	84	83	72	83	83	79	60	67
VTT+METLA/Mass	W,L	Global density	26	26	27	32	21	15	50	48	50	61	38	45	89	92	92	91	78	87
VTT+METLA/TKAR	I	TKAR	20	25	33	43	45	24	18	15	16	33	42	14	4	4	3	12	7	1
VTT+METLA/Knot	W,L,I	TKAR+Global dens.	40	45	53	57	56	36	61	56	60	73	67	55	89	92	92	91	79	87

*) For Raute/Flatwise stiffness the r^2 value of all sizes is an average of the separate values.

Table 17. Coefficient of determination r^2 of individual NDT-measurements or combined ones (grading machines IP's) to destructively determined properties in bending for pine. NDT-measurement type codes: L = length, W = weighing, F = natural frequency, X = X-ray (X_D = Xray with only density used), U = Ultrasonic, R = Electric Resistance (for moisture content), B = Bending stiffness, V = Dimensions (Length and Volume), I = Visual inspection.

BENDING		destruct. r^2 of / to:	Strength, MOR						Stiffness, MOE-Glob.						Density; Ru					
PINE Source	Meas. incl.	Size	ALL	38x100	50x100	50x150	44x200	63x200	ALL	38x100	50x100	50x150	44x200	63x200	ALL	38x100	50x100	50x150	44x200	63x200
Destructive		MOR	100	100	100	100	100	100	70	75	79	72	72	73	41	56	53	51	44	43
Destructive		MOE-Global	70	75	79	72	72	73	100	100	100	100	100	100	59	66	63	64	58	49
Destructive		Dens, Ru	41	56	53	51	44	43	59	66	63	64	58	49	100	100	100	100	100	100
Bintec/Log X-ray	X	Log-X knot A	33	34	35	43	45	56	38	35	33	37	46	43	25	19	17	20	34	26
Bintec/Log X-ray	X	Log-X knot B	2	14	2	2	4	0	0	13	3	3	3	0	3	4	0	0	7	1
Bintec/Log X-ray	X	Log-X knot C	43	45	48	45	46	52	39	37	39	35	43	41	31	30	30	26	37	29
Bintec/Log X-ray	X	Log-X density sapw.	6	1	27	17	25	40	8	1	25	16	29	39	10	0	38	22	28	39
Bintec/Log X-ray	X	Log-X density heartw	23	10	42	37	45	48	24	8	44	39	54	58	29	8	65	53	58	67
Bintec/Log X-ray	X	Log-X annual ring	16	11	17	27	17	14	8	12	13	23	15	14	4	7	11	19	16	9
Bintec/Log X-ray	X	Log-X all	58	61	64	65	58	70	57	59	66	64	64	70	57	63	72	62	63	72
Fibregen/Log-Freq.	F,L	Log-Edyn (Freq.)	21	10	27	25	28	21	37	25	42	48	49	45	14	12	15	30	21	17
VTT+METLA/Log-Den.	W,V	Log-Dens	11	12	5	13	15	14	7	10	5	14	19	20	7	25	11	22	18	13
VTT+METLA/Log-	F,L	Log-Edyn(Freq.)	25	10	25	23	37	47	37	27	45	45	51	71	15	5	15	28	23	38
VTT+METLA/Log-Edy.	F,W,V	Log-Edyn	31	34	22	32	39	45	35	52	33	52	54	66	20	42	24	44	31	38
VTT+METLA/Log-US	U,L	Log-US	24	15	24	21	33	47	44	35	43	45	46	73	19	11	17	20	19	32
VTT+METLA/Log-Edy.	U,W,V	Log-Edyn(US+dens)	33	37	23	38	35	45	42	54	33	63	47	69	25	50	25	47	27	34
Raute/flatwise stiffn.	B	Raute Estat (flatwise)	(68)	69	69	64	72	63	(79)	84	82	79	78	71	(58)	61	63	64	52	51
CBS-CBT/Ultrasonic	U,R,L	US-speed	58	58	68	60	63	66	65	73	74	68	69	67	35	41	40	46	41	34

BENDING		destruct. r^2 of / to:	Strength, MOR						Stiffness, MOE-Glob.						Density; Ru					
PINE Source	Meas. incl.	Size	ALL	38x100	50x100	50x150	44x200	63x200	ALL	38x100	50x100	50x150	44x200	63x200	ALL	38x100	50x100	50x150	44x200	63x200
CBS-CBT/Ultrasonic	U,R,L	US-peak	4	1	3	4	19	12	1	0	5	2	29	14	0	0	5	0	18	2
CBS-CBT/Ultrasonic	R,L	Dens. (Hardness)	13	10	19	8	23	14	17	12	24	15	25	16	20	19	31	21	19	19
CBS-CBT/Ultrasonic	U,R,L	I.P.	60	59	69	62	66	68	68	74	76	69	72	70	44	50	48	50	42	39
MiCROTEC/Freq.	F,L	Edyn1(Freq)	57	51	64	55	65	63	71	74	76	76	83	78	28	35	36	37	39	27
MiCROTEC/Freq.+den	F,X_D,L	Edyn1(Freq.+dens.)	69	70	76	68	72	71	89	90	90	91	93	91	61	73	71	69	61	55
MiCROTEC/X-ray	X_D	X-ray aver density	49	59	56	52	55	45	67	66	68	67	74	61	80	89	89	84	76	71
MiCROTEC/X-ray	X_D	X-ray min density	50	54	56	50	59	48	69	63	67	67	78	66	74	86	84	81	66	65
MiCROTEC/X-ray	X_D	X-ray clear density	53	63	59	56	59	51	71	70	71	71	77	66	81	90	89	85	77	72
MiCROTEC/X-ray	X	X-ray knot a	57	51	62	63	59	67	54	47	53	55	64	54	39	32	38	43	51	33
MiCROTEC/X-ray	X	X-ray knot b	59	51	59	66	60	73	54	49	49	56	60	57	34	30	28	36	45	30
MiCROTEC/X-ray	X	X-ray knot c	60	58	65	68	60	73	57	51	54	60	61	59	39	35	34	41	49	31
MiCROTEC/X-ray	X	X-ray knot d	59	46	58	65	60	77	54	46	52	53	59	60	35	29	29	37	46	33
MiCROTEC/X-ray	X	X-ray I.P.	69	68	75	74	69	78	78	73	77	78	82	78	81	90	89	85	77	73
MiCROTEC/Freq.+X-r	F,X,L	Edyn1 + X-ray I.P.	75	75	82	78	75	82	90	91	91	92	93	91	81	90	89	85	77	73
TNO/Brookhuis	F,L	Edyn2 (Freq.)	51	45	50	52	63	61	63	67	61	69	82	74	23	30	26	37	37	26
TNO/Brookhuis	W,L	Global density	46	57	49	53	52	41	63	62	61	65	70	58	78	87	84	82	75	72
TNO/Brookhuis	F,W,L	Edyn2(Fr+D.)-IP MOE	66	69	72	68	70	70	89	89	87	91	93	91	62	72	68	68	62	55
TNO/Brookhuis	F,W,L	Edyn2(Fr+D.)-IP MOR	60	70	69	68	69	67	86	86	84	89	92	88	74	83	80	78	70	66
VTT+METLA/Mass	W,L	Global density	39	31	52	47	51	43	57	38	63	65	69	58	71	53	86	78	75	72
VTT+METLA/TKAR	I	TKAR	41	37	57	60	57	68	46	35	45	49	61	55	32	19	22	36	47	28
VTT+METLA/Knot	W,L,I	TKAR+Global dens.	56	62	74	70	65	76	72	67	74	75	78	75	56	62	74	70	65	76

(*) For Raute/Flatwise stiffness the r^2 value of all sizes is an average of the value of different sizes.

Table 18. Coefficient of determination r^2 of individual NDT-measurements or combined ones (grading machine IP's) to destructively determined properties in tension for spruce. NDT-measurement type codes: L = length, W = weighing, F = natural frequency, X = X-ray (X_D = Xray with only density used), U = Ultrasonic, R = Electric Resistance (for moisture content), B = Bending stiffness, V = Dimensions (Length and Volume), I = Visual inspection.

TENSION		destruct. r^2 of / to:	Strength						Stiffness, MOE						Density; Ru					
SPRUCE Source	Meas. incl.	Size	ALL	38x100	50x100	50x150	44x200	63x200	ALL	38x100	50x100	50x150	44x200	63x200	ALL	38x100	50x100	50x150	44x200	63x200
Destructive		MOR	10	10	10	10	10		57	53	52	65	56		28	30	17	33	28	10
Destructive		MOE-Global	57	53	52	65	56		10	10	10	10	10		57	53	52	62	61	57
Destructive		Dens, Ru	28	30	17	33	28		57	53	52	62	61		10	10	10	10	10	28
Bintec/Log X-ray	X	Log-X knot A	15	19	26	26	24		8	5	12	20	13		2	1	2	10	8	
Bintec/Log X-ray	X	Log-X knot B	15	12	14	21	7		7	2	9	14	2		3	2	1	5	0	
Bintec/Log X-ray	X	Log-X knot C	19	26	24	27	21		9	11	11	18	8		5	9	4	9	8	
Bintec/Log X-ray	X	Log-X density sapw.	0	0	1	2	2		2	3	1	0	6		7	9	4	2	13	
Bintec/Log X-ray	X	Log-X density	6	5	1	5	4		15	11	13	14	21		38	32	39	37	47	
Bintec/Log X-ray	X	Log-X annual ring	11	6	5	18	11		5	5	4	6	5		2	1	1	3	1	
Bintec/Log X-ray	X	Log-X all	42	44	39	52	37		39	34	47	53	43		57	59	65	62	60	
Fibregen/Log-Freq.	F,L	Log-Edyn (Freq.)	14	3	18	23	29		26	9	27	36	48		9	0	12	19	31	
VTT+METLA/Log-	W,V	Log-Dens	6	4	0	13	3		4	7	1	13	2		4	9	0	4	0	
VTT+METLA/Log-	F,L	Log-Edyn(Freq.)	7	4	0	18	3		4	5	1	14	0		2	3	0	4	5	
VTT+METLA/Log-	F,W,V	Log-Edyn	0	0	1	4	0		1	2	0	1	2		4	6	4	0	8	
VTT+METLA/Log-	U,L	Log-US	16	13	21	24	34		26	19	33	37	55		7	2	6	17	22	
VTT+METLA/Log-	U,W,V	Log-	12	13	4	20	17		27	31	20	42	43		16	16	13	25	31	
Raute/flatwise stiffn.	B	Raute Estat	(58	61	55	60	55		(77	79	78	74	78		(59	63	52	60	62	

TENSION		destruct. r^2 of / to:	Strength						Stiffness, MOE						Density; Ru					
SPRUCE Source	Meas. incl.	Size	ALL	38x100	50x100	50x150	44x200	63x200	ALL	38x100	50x100	50x150	44x200	63x200	ALL	38x100	50x100	50x150	44x200	63x200
CBS-CBT/Ultrasonic	U,R,L	US-speed	51	47	45	52	58		55	48	55	51	63		13	12	6	15	19	
CBS-CBT/Ultrasonic	U,R,L	US-peak	0	0	0	6	3		0	0	1	10	2		1	1	0	2	1	
CBS-CBT/Ultrasonic	R,L	Dens. (Hardness)	13	20	13	6	12		24	20	23	21	38		42	35	42	44	54	
CBS-CBT/Ultrasonic	U,R,L	I.P.	58	57	55	54	61		63	46	68	62	77		47	39	45	47	61	
MiCROTEC/Freq.	F,L	Edyn1(Freq)	53	50	47	61	61		64	56	60	71	75		14	13	7	21	21	
MiCROTEC/Freq.+d	F,X_D,L	Edyn1(Freq.+dens.)	58	58	51	62	57		91	84	91	93	95		65	67	58	71	64	
MiCROTEC/X-ray	X_D	X-ray aver density	24	24	18	28	18		54	51	51	61	54		91	90	90	92	91	
MiCROTEC/X-ray	X_D	X-ray min density	29	31	21	36	24		61	57	59	69	62		89	91	83	90	92	
MiCROTEC/X-ray	X_D	X-ray clear density	28	29	21	32	23		58	55	56	65	60		92	92	90	93	93	
MiCROTEC/X-ray	X	X-ray knot a	38	37	38	42	42		32	32	37	36	29		17	16	14	23	15	
MiCROTEC/X-ray	X	X-ray knot b	38	33	37	35	47		32	27	34	34	33		14	11	10	19	15	
MiCROTEC/X-ray	X	X-ray knot c	39	34	40	39	42		30	24	37	33	26		16	13	14	19	16	
MiCROTEC/X-ray	X	X-ray knot d	38	28	34	37	45		30	21	29	33	31		12	7	7	17	14	
MiCROTEC/X-ray	X	X-ray I.P.	49	49	41	53	51		69	66	68	74	71		92	92	90	93	93	
MiCROTEC/Freq.+X	F,X,L	Edyn1 + X-ray I.P.	64	64	58	69	68		91	84	91	93	95		92	92	90	93	93	
TNO/Brookhuis	F,L	Edyn2 (Freq.)	50	48	45	59	55		61	56	56	65	70		11	12	5	15	17	
TNO/Brookhuis	W,L	Global density	21	25	18	25	14		50	50	51	53	47		86	89	90	79	87	
TNO/Brookhuis	F,W,L	Edyn2(Fr+D.)-IP	54	58	52	61	55		88	85	91	89	94		58	67	55	60	62	
TNO/Brookhuis	F,W,L	Edyn2(Fr+D.)-IP	43	50	43	52	46		78	80	85	84	90		69	81	74	72	77	
VTT+METLA/Mass	W,L	Global density	25	26	17	30	22		55	52	51	62	57		90	91	87	90	92	
VTT+METLA/TKAR	I	TKAR	18	23	11	27	32		9	8	10	17	13		1	0	2	3	1	
VTT+METLA/Knot	W,L,I	TKAR+Global dens.	43	48	26	51	54		64	60	59	72	70		91	90	87	92	93	

*) For Raute/Flatwise stiffness the r^2 value of all sizes is an average of the separate values.

5. Discussion and conclusions

5.1 Sampling

The sampling of logs and sawn timber used in this work was comprehensive and gave a large and representative sample of both logs and sawn timber from the intended area – Finland and North-Western Russia. The large sample size, approx. 1000 pieces of both species was so chosen that enough data should be retained corresponding to the requirements of machine control approval, which requires a minimum of 900 specimens (EN 14081, CEN 2005). The high number of specimens and distributed gathering ensured well the variability of the sample.

The average values and coefficients of variation of the destructively obtained properties of *spruce* are at the same level as in some previous studies (Ranta-Maunus et al. 2001). However, the *pine* timber in this study was clearly of lower density and strength than could be anticipated. This is to a large extend explained by the low density of the material obtained from Russia. The reason for this low density is not clear.

It may be said that on average the pine used here has been lighter and weaker than expected and that spruce is of approximately the same level as in previous studies.

5.2 Correlations of single parameters

5.2.1 Destructively determined parameters

The correlations between destructively determined properties (Table 12 and Table 13) can be used as a baseline when assessing the correlations of the NDT-parameters. As was already recognized in Combigrade-1 with a smaller sample size, spruce and pine do show clearly different behaviour in regard to what are the correlation of strength and stiffness to each other and to NDT-parameters. This is now confirmed by the large sample size. Both the correlations of destructive measured parameter and the NDT-parameters (Table 16 and

Table 17) show in most cases clearly higher r^2 values for pine than for spruce. Therefore the treatment of the two species separately is the only reasonable way to examine the results. Also, the behaviour of the different cross-sections is in many cases quite different so that the treatment of the sizes as separate is reasonable.

It is also worthwhile to note the very high correlation between the destructive determined stiffness and strength of pine. This is probably due to the good sampling and consequent high variability in the material.

As the destructive tests contained several cross-section sizes, they give the possibility to draw conclusions of how the size affects correlations. As a general trend the following can be said: For both spruce and pine, the correlation of density to bending strength and stiffness reduces when cross-section size increases. However this does not apply to tension strength and stiffness.

Comparison between bending and tension (spruce)

In general, it can be said that stiffness shows a slightly better correlations to bending strength than to tension strength. Density, however, shows approximately similar correlations in both loading modes.

The consideration of the NDT-parameters has been dealt with in the following by categorising them into five classes: stiffness, density parameters, knot parameters, X-ray parameters and other board measurement results. Parameters measured on logs are dealt with separately.

5.2.2 Stiffness parameters (boards)

The stiffness related NDT-parameters (flatwise E_{stat}, E_{dyn}, US-speed) naturally show the highest single-variable correlations to the stiffness in destructive tests. They are also among the best in correlations to bending strength (MOR r^2 values around 0.5–0.8). Quite satisfactory is also their prediction capability to the density of pine. The effectiveness of E_{dyn} is increased, if it is calculated based on a measured density value [E_{dyn}(Freq.&Dens.), E_{dyn}(US&Dens.)] than on default density [E_{dyn}(Freq.), E_{dyn}(US)] only. This is maybe more important for spruce, because the correlation is otherwise low. But, it must be remembered that this in effect means the combination of two measurements.

The results also indicate that natural frequency and US-speed have a higher correlation to tension strength than to bending strength.

5.2.3 Density parameters (boards)

The non-destructive average density parameters, measured either by weighing or X-ray have correlations to bending strength rather close to each other with r^2 around 0.15–0.3 for spruce and 0.4–0.6 for pine (the clear or minimum density measured with X-ray even has slightly higher value for both species). These values are of the same magnitude or even higher than the destructively determined density itself has. It can be concluded that density as a physical variable determines the bending strength up to this amount. Notable is that for pine density is a much better predictor of strength than for spruce and that the correlations to bending and tension strength of spruce are of very similar magnitude.

Density parameters typically give some 0.2–0.3 higher r^2 values for correlations to stiffness than they give to strength. The fact, that stiffness is a global property contrary to strength and therefore more dependent on density, is confirmed again here. Once again, pine gets clearly higher correlations than spruce.

5.2.4 Knot parameters (boards)

Knot parameters can be determined in many ways. In this study, the knot parameters which were determined by irradiation (X-rays) performed better than the parameters that were determined with only surface inspection (TKAR), when predicting strength. Noteworthily, the much higher r^2 values for pine than spruce show that knots determine a far greater percentage of the bending strength of pine than of spruce.

By knots, even the stiffness and density of pine can be rather well predicted, especially some cross-section sizes (r^2 values even around 0.5). For spruce, on the contrary, the correlation of TKAR to density is on the average poor. Its correlation to stiffness seems to be depended on the form of the cross-section: the narrow cross sections (44x200 and 50x150) show higher correlation. It might be possible to improve the correlations by improved knot parameter definitions, e.g. knot cluster (Fonselius et al. 1997).

5.2.5 Combination of stiffness and density parameter (boards)

The addition some kind of density measurement improves the results of stiffness related parameters. This is more important for spruce for which the correlation is otherwise low.

5.2.6 X-ray parameters together (boards)

The combination of all X-ray parameters could in fact be considered a single parameter, because all X-ray results are available immediately after the one measurement run. The X-ray measurement parameters together achieve the same level of correlation as the best stiffness related single parameters. Moreover, the X-ray scan provides the information on the location of knots, which can help to cut out big knots or knot clusters out of the boards in order to upgrade the timber.

5.2.7 Log measurements

A surprising result already obtained in the Combigrade-Part 1 was the high correlations that can be reached by the log measurements to the properties that were measured destructively from the sawn boards or planks. The results of the larger sample in Part 2 now confirms the result. The combination parameters measured by log X-ray can reach as high r^2 value as 0.6–0.7 depending on the cross-section size for pine. The result is not as good for spruce, but can still reach as high r^2 value as 0.4–0.5. However, it is important to notice that all parameters obtained from the Log X-ray measurements are readily available at the same time, so their combined analysis is without further measurement efforts available.

The dynamic MOE based on natural frequency measurement or speed of ultrasonic sound correlates to the stiffness of the boards with a relatively high r^2 value.

5.3 Conclusion about correlations

It should be emphasized that the correlations and r^2 values given above is not a direct measure of the strength grading effectiveness, because the actual effectiveness of the system may depend on whether the variation occurs in low or high strength side and on the capability of the method to pick out the very weak pieces by some other way. Therefore small differences of r^2 values should not be used as indication of superiority of a certain method compared to another.

Based on the r^2-values of the combined analyses (Table 16 and Table 17), it can be said on a general level, that combining two sufficiently different measurements raises the r^2 value in many cases by about 0.1. It is difficult to improve greatly the already high r^2-values with auxiliary parameters. Density and knot measurements together seem to be a rather effective combination especially for pine. It increases the r^2 values to above 0.5 for spruce and to 0.7 for pine.

The results of the correlation analyses give remarkably similar conclusions that were already got in the Combigrade-Part 1 with a smaller sample. As already given in the report of Combigrade-1 the main conclusions on correlations are compactly summarized in Table 19, which is reproduced here in a modified content. The middle column serves as a “vertical axis” containing r^2-ranges in order and chosen single NDT-methods and their combinations are placed on both sides of the “vertical axes” beside the r^2 range that they could reach in the measurements of this project. The values for spruce are on the left side of the “axis” and pine on the right.

Table 19. A summary of the correlation analysis results. Raute = static stiffness by Raute Timgrader machine, E_{dyn} values represent values calculated with default density = E_{dyn}(Freq). **Single measurements** *with boldface, logical operators AND/OR used for description of combinations.*

Spruce	r^2 range	**Pine**
	...0,8 0,7...	**Ultrasound**, **Raute**, **Board X-ray**, E_{dyn} AND knot
E_{dyn} AND Board X-ray	...0,7 0,6...	E_{dyn} AND density **Log X-ray** **E_{dyn}**
E_{dyn} AND dens., **Raute**, **Board X-ray**, US AND dens.	...0,6 0,5...	**knot**, log E_{dyn} AND density **density**
US, E_{dyn}, **Log X-ray**,	...0,5 0,4...	log E_{dyn} AND ring width
density,	...0,4 0,3...	**log E_{dyn}**
knot, log E_{dyn}	...0,3 0,2...	

6. Summary

6.1 General

The quality of a strength grading system is determined principally by (1) the ability of the measured parameter(s) to predict strength (2) the measurement error of the predictor parameter(s) and (3) the capability of the system to sort-out very diverging pieces with low strength in some way. The first factor can be quantified by regression analysis (the obtained coefficient of determination, r^2) and the second by the coefficient of variation V of the measurement error. If the regression analysis is based on measurements made in the same conditions and the same apparatus that is used in the strength grading machine, the effect of the measurement error and V is already included in the r^2 value directly. Otherwise, if the measurements are made in laboratory conditions, the effect of measurement error should be considered separately, when evaluating the effectiveness of a certain strength grading system.

In the present study, various non-destructive test (NDT) methods were applied to a large sample – approx. 1000 spruce and 1000 pine specimens with cross section dimensions 38x100, 50x100, 50x150, 44x200 and 63x200. From these measurements some 30 NDT-parameters were extracted. After the NDT-measurements the specimens were tested in destructive loading to obtain the bending strength, stiffness and density values of each specimen. All these three properties are grade determining properties in the European system of timber strength classes. Part of the specimens went to tension tests in a parallel project and the tension strength, modulus of elasticity and density was obtained for them. Based on regression analyses, the r^2-values of the single NDT-parameters and their combinations were obtained in regard to all three grade determining properties.

The sample size used was large, which makes the results particularly valuable. As a difficulty in comparing the results of different measurements, the different measurements were not made in similar conditions. Some of them were made in laboratory conditions and some in true industrial conditions (the conditions of each measurement are explained in Section 3.2). Thus, the results presented should not be used as definitive ranking of the methods.

6.2 Evaluation of different methods

Small differences of r^2 values should not be used as indication of superiority of a certain method compared to another due to reasons explained above. Furthermore, when considering the fitness of a strength grading system to a certain application, the evaluation of the prediction accuracy in terms of r^2 and V is not adequate alone. Obviously, the price of the system, its fitness to production line and target strength classes are other important factors.

Out of the three grade determining properties, the bending strength is in most cases the critical one. Therefore, in the following outline only correlations with respect to it are considered.

The present results with a large sample confirm to great extent the conclusions already obtained with the small sample in Part 1 of this project (Hanhijärvi et al. 2005). In fact, the results are surprisingly similar, considering the low number of specimens in Part one (appr. one hundred per species). Nevertheless, this does not reduce the value of the new results, since without a statistically sound sampling any conclusions are not reliable.

Based on the results, it can be said that the best single parameter predictors of bending strength are the stiffness related parameters (modulus of elasticity [MOE]) measured by either static method, vibration method or by ultrasonic method. However, X-ray scanning of boards (with several measured quantities) as a single measurement reaches the same level. As single methods for predicting strength these can reach r^2 values of 0.5–0.6 for spruce and 0.7–0.75 for pine. It is difficult to improve dramatically their r^2 values with auxiliary measurements. However, combining stiffness parameters with knot or density measurements or X-ray measurement with stiffness parameters does improve the result enough to be profitable.

Density as measured by different methods (direct weighing, X-ray irradiation) can reach r^2 values 0.3–0.4 for spruce and 0.5–0.6 for pine. Combination to knot measurement increases the r^2 values to above 0.5 for spruce and to 0.7 for pine.

The ability of knots to predict strength is greatly different for spruce and pine having correlations with r^2-values of c 0.15–0.3 and approx. 0.35–0.6, respectively. If knot measurement is supplemented by density or annual ring width measurement, r^2 values show clearly higher results: 0.45–0.5 for spruce and 0.6–0.7 for pine.

The log measurements showed surprisingly high correlations to strength, even if their development for strength grading is very preliminary so far. So, it seems they have potential in this respect. The log X-ray could reach an r^2 value of 0.3–0.5 for spruce strength and around 0.65 for pine strength.

As stated in many instants above, practically all methods give higher coefficient of determination with strength of pine than strength of spruce. It should be noticed that in general this does not indicate that yield with grading of pine would be better than with spruce. Larger knot sizes of pine result in larger portion of material belonging to low strength classes.

Acknowledgements

The project is financed by Tekes – Finnish Funding Agency for Technology and Innovation, Wood Focus Finland and VTT which is gratefully acknowledged.

References

CEN 2003a. European Standard EN338. Structural Timber – Strength classes. CEN – European Committee for Standardization. Brussels.

CEN 2005. European Standard EN 14081-1...4. Timber structures – Strength graded structural timber with rectangular cross section.

CEN 2006. European Standard EN14081-1...4. Timber structures – Strength graded structural timber with rectangular cross section.

Fonselius, M., Lindgren, C. & Makkonen, O. 1997. Lujuuslajittelu nostaa jalostusarvoa. – Suomalaisen sahatavaran lujuus. Rakentavaa Tietoa 16.5.1997. Espoo: VTT Rakennustekniikka. (In Finnish.)

Giudiceandrea, F. 2005. Stress grading lumber by a combination of vibration stress waves and x-ray scanning. Proc. of Scan Tech 2005, International Conf. Las Vegas, NV, USA.

Glos, P. 1995. Solid timber – Strength classes. STEP lecture A7. In: Timber Engineering STEP 1. Centrum Hout, Almere, the Netherlands.

Hanhijärvi, A., Ranta-Maunus, A. & Turk, G. 2005. Potential of strength grading of timber with combined measurement techniques. Report of the Combigrade-project – phase 1. VTT Publications 568. Espoo: VTT. ISBN 951-38-6647-5. 81 p. + app. 6 p. Available http://www.vtt.fi/inf/pdf/publications/2005/P568.pdf.

Poussa, M., Tukiainen, P., Mitsuhashi, K. & Andersin, P. 2007. COMBI T – Destructive tension, shear, and compression (0° and 90°) strength tests for Finnish sawn timber. Helsinki University of Technology, Laboratory of Structural Engineering and Building Physics Publication TKK-TRT-130. Available http://www.tkk.fi/Yksikot/Talo/projektit/COMBI_T.pdf.

Ranta-Maunus, A. 2007. Strength of Finnish grown timber. VTT Publications 668. Espoo: VTT. 60 p. + app. 3 p. Available http://www.vtt.fi/inf/pdf/publications/2007/P668.pdf.

Ranta-Maunus, A., Fonselius, M., Kurkela, J. & Toratti, T. 2001. Reliability analysis of timber structures. VTT Tiedotteita – Research Notes 2109. Espoo: VTT. 102 p. + app. 3 p. Available http://www.vtt.fi/inf/pdf/tiedotteet/2001/T2109.pdf.

Sandoz, J.L. 1989. Grading of construction timber by ultrasound. Wood Science and Technology 23, pp. 95–108.

Sandoz, J.L. 1996. Ultrasonic solid wood evaluation in industrial applications. In: Sandoz, J.L. (ed.) Proc. 10th International Symposium on Nondestructive Testing of Wood. Lausanne Aug. 26–28, 1996. Lausanne, Presses polytechniques et universitaires romandes.

Other literature

Blass, H. & Gard, W. 1994. Machine strength grading of timber. Proceedings of Pacific Timber Engineering Conference, Gold Coast Australia, July 11–15, pp. 598–603.

CEN 1995. European Standard EN384. Structural Timber – Determination of characteristic values of mechanical properties and density. CEN – European Committee for Standardization. Brussels.

CEN 1999. European Standard EN1194. Timber Structures – Glued laminated timber – Strength classes and determination of characteristic values. CEN – European Committee for Standardization. Brussels.

CEN 2003b. European Standard EN408. Timber Structures – Structural timber and glued laminated timber – Determination of some physical and mechanical properties. CEN – European Committee for Standardization. Brussels.

Glos, P. 2004. New grading methods. Proceedings of COST E29 Symposioum, Florence Oct. 27–29. CNR-Ivalsa, San Michele all'Adige, Italy. Pp. 1–8.

Görlacher, R. 1984. Ein neues Messverfahren zur bestimmung des Elastizitäts-moduls von Holz. Holz als Roh- und Werkstoff 42, pp. 219–222.

Hoffmeyer, P. 1995. Styrkesortering ger mervärde. Del 2 – Tilgaengelig teknik. Laboratoriet for Bygningsmaterialer, Danmarks Tekniske Universitetet, Teknisk Rapport 335. (In Danish.)

Johansson, C.-J., Brundin J. & Gruber R. 1992. Stress grading of Swedish and German timber. A comparison of machine stress grading and three visual grading systems. SP Report 1992:23. Swedish National Testing and Research Institute Building Technology.

Series title, number and report code of publication

VTT Publications 686
VTT-PUBS-686

Author(s)
Hanhijärvi, Antti & Ranta-Maunus, Alpo

Title

Development of strength grading of timber using combined measurement techniques
Report of the Combigrade-project – phase 2

Abstract

More than 1000 pieces of spruce (*Picea abies*) logs and 1000 pieces of pine (*Pinus sylvestris*) logs were sampled mostly from Finland but also from North-Western Russia. Non-destructive measurements were first made on the logs and sawn timber of five different cross-section sizes were produced by sawing and kiln drying. Next, the sawn timber boards and planks went through several non-destructive measurements. NDT-measurements were made by 7 organisations producing some 50 different measured quantities of both logs and of each test piece. Finally, after all the non-destructive measurements, the test material was loaded to failure in bending, and grade determining properties (modulus of elasticity, bending strength and density) were measured. Degrees of determination were calculated between the non-destructively measured indicators and grade determining properties.

It could be concluded that the coefficients of determination – the r^2 values – between strength and most non-destructive indicators were remarkably higher for pine than for spruce. Especially, knot size and density are better grading parameters for pine than for spruce. This does not, however, indicate that yield to high grades would be in general better with pine than spruce, but it indicates that pine has larger variability of knot sizes and density, and consequently higher variability of strength. Log scanning can also produce strength indicators which are on the same level as some existing grading methods.

In parallel to this project another project that dealt primarily with grading of spruce based on tension strength was carried out and some results of that project are also reported.

ISBN
978-951-38-7106-2 (URL: http://www.vtt.fi/publications/index.jsp)

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

Project number

Date	Language	Pages
August 2008	English	55 p.

Name of project	Commissioned by
Combigrade 2	Tekes, Wood Focus Finland, VTT

Keywords
strength grading, combined measurement techniques, sawn timber, bending strength, non destructive testing, X-ray scanning, frequency measurement, ultrasonic transit time, acoustic-ultrasonic measurement, destructive strength, stiffness, density

Publisher
VTT Technical Research Centre of Finland
P.O. Box 1000, FI-02044 VTT, Finland
Phone internat. +358 20 722 4520
Fax +358 20 722 4374

VTT PUBLICATIONS 686

Development of strength grading of timber using combined measurement techniques

This publication documents the results of the second part of "Combigrade"-project. 1000 pieces of both spruce (*Picea abies*) logs and pine (*Pinus sylvestris*) logs were sampled and sawn timber produced. Non-destructive measurements of logs and sawn timber were made by 15 organisations producing 20 different measured quantities for each test piece. Finally, test material was loaded to failure in bending, and grade determining properties (modulus of elasticity, bending strength and density) were measured. Coefficients of determination were calculated between non-destructively measured indicators and grade determining properties.

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

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

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

ISBN 978-951-38-7106-2 (URL: http://www.vtt.fi/publications/index.jsp)
ISSN 1455-0849 (URL: http://www.vtt.fi/publications/index.jsp)