 DOI 10.1515/hf-2013-0042 — Holzforschung 2014; 68(2): 203–216

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Efficiency of visual strength grading of timber with respect to origin, species, cross section, and grading rules: a critical evaluation of the common standards

Abstract: Strength grading is essential for the efficient use of structural timber. Although international standards exist for machine strength grading, visual grading is still regulated based on national rules, which are expected to allow safe and economic grading results. Although there are large differences in the graded output because the species, the cross section, and the origin of the timber influence the results, some of these standards are considered to be applicable universally. The present article demonstrates how the chosen standards influence the grading results. Depending on the parameters, the yields or the mechanical properties are low compared with the declared values. The results also show the efficiency and applicability of different national standards for strength grading of timber from various origins. Furthermore, it is recommended to reconsider the existing limits for source areas and cross sections given in the standard EN 1912.

Keywords: grading standard, mechanical properties, sawn timber, timber grading, timber source

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Introduction

The major part of structural timber on the European market is graded visually. While European standards are commonly used (EN 14081-2 and EN 14081-3) for machine-graded timber, visual grading is done mainly based on national standards. These national standards are supposed to optimize the grading results for the timber resources of the country, taking into account growth conditions, local preferences for certain cross sections, silvicultural differences, and historical developments concerning structural applications. National grading rules are assessing differently the knot size, growth ring width, or (local) slope of grain. Depending on the standard, the raw material can be graded into up to four grades, for instance, according to the Scandinavian standard INSTA 142.

To facilitate the exchange structural timber between different markets, European standard EN 1912 lists how national grades are related to strength classes as given in EN 338. Assignments are restricted not only for certain species but also for geographical areas or certain cross sections for which the national grading rules are valid. For additional entries in EN 1912, scientific reports or a proven record of long experience are required concerning a certain wood species in its application. It is required that the test material be representative for the whole population with regard to timber source, sizes, and qualities. To cover these aspects, physical testing usually requires a considerable amount of test pieces. A large variation in physical properties is to be expected, as wood species generally grow over large geographical areas on different soils and under various climatic conditions.

The testing efforts of today are in contrast to the assignments that have been introduced 15 years ago, when the European market was created. For some grading standards, large growth areas were specified at the same time. An extreme example is spruce originating from the growth area Central, North, and Eastern Europe (CNE Europe).

There are only a few publications focusing on the comparison of national grading rules. Johansson et al. (1992) compared INSTA, DIN, and ECE rules. Spruce timber from Germany and Sweden (SE) was graded and tested in bending (255 pieces) and tension (245 pieces). When compared with published strength values for the highest grade of INSTA and DIN, the reached bending strength values were much higher than the declared values. INSTA T3 class reached a 5% characteristic bending strength of 38.5 MPa and DIN S13 class reached 36.9 MPa in bending, as compared with 30 MPa declared

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for both grades. Also, all lower classes showed significantly higher values than expected from the current strength class assignments in EN 1912. Similar effects were found for modulus of elasticity (MoE) and density. However, the results were not analyzed separately for the different origins. Small-scale comparisons for a limited number of specimens were carried out by Almazán et al. (2008) for German pine graded by DIN 4074 and UNE 56544 or by Riberholt (2008) for European spruce graded according to Chinese visual rules. Visual grading is addressed in several available CIB-W18 timber structures publications (Fewell 1984; Uzielli 1986; Barrett et al. 1992; Stapel et al. 2010), but none of these focused on the comparison of different grading rules and the assignment according to EN 1912.

Verification of the validity of grading standards for such large growth areas as CNE is the main goal of the present article. Softwoods (spruce, pine, larch, Douglas fir, and Sitka spruce) will be graded and tested in tension or by edgewise bending. The following grading standards will be in focus: DIN 4074-1:2012-06, BS 4978:2007+A1:2011, DS/INSTA 142:2009 (E), NF B 52-001-1:2011, and SIA 265/1:2009. Three main factors will be analyzed, with particular emphasis on the available cross sections, the applied grading standards, and the geographical source of the timber.

Table 1 List of symbols and abbreviations.

Symbol	Definition
BS	British visual grading standard
CE	Central Europe
CH	Switzerland
CNE	Central, North, and Eastern Europe
cov	Coefficient of variation
DEK	Important knot parameter used for DIN grading
DIN	German visual grading standard
DIN-B	Grading rules for boards given in DIN
DIN-K	Grading rules for joists given in DIN
E_0	Modulus of elasticity (MPa)
$E_{0,mean}$	Modulus of elasticity, mean value (MPa)
EE	Eastern Europe
f_m	Bending strength (MPa)
$f_{m,k}$	Bending strength, 5th percentile value (MPa)
FI	Finland
FR	France
f_t	Tension strength (MPa)
$f_{t,k}$	Tension strength, 5th percentile value (MPa)
INSTA	Scandinavian visual grading standard
LV	Latvia
MoE	Modulus of elasticity
n	Number of specimens
NF	French visual grading standard
PL	Poland
RU	Russia
R^2	Coefficient of determination
ρ	Density (kg m^{-3})
ρ_k	Density – 5th percentile value (kg m^{-3})
SE	Sweden
SI	Slovenia
SIA	Swiss visual grading standard
SKA	Single-knot data are available
tKAR	Total knot area ratio
UK	United Kingdom

Materials and methods

A total of 12 837 specimens were analyzed. The data set is divided for two loading modes (edgewise bending and tension) and for two knot descriptions. In 60% of all cases, every single knot of the specimen was measured, and this is classified as single knots available (SKA, abbreviations are summarized in Table 1). These SKA data formed the basis for analyzing the influence of the cross section and the grading standard. For the remaining 40%, no single-knot data were available, but the total (largest) knot area ratio (tKAR) could be measured. The influence of the geographical source of the timber was analyzed based on the tKAR data. Table 2 summarizes the available data sets. The used material was sampled on sawmill level. No requirements for the log quality were defined, but regional available logs were used. The boards of the logs are considered as sawfalling material, which is in line with the procedure used for the derivation of mechanical properties of sawn timber or the derivation of machine settings. All specimens with available SKA values were tested at Holzforschung München between 1995 and 2012. The remaining specimens were tested at various laboratories around Europe during the Gradewood project, which finished in 2011 (Ranta-Maunus et al. 2011).

Destructive tests were performed according to EN 408:2010 for both bending (symmetrical two point loading; span: 18 times the depth) and tension (span: 9 times the depth). The orientation of the board in edgewise bending tests was chosen randomly. The modification factors for test setup and specimen sizes given in EN 384:2010 have been applied (k_h is the factor for depth and k_l is the factor for length). Whenever possible, the weakest section along the beam axis was tested. The original beam length from which the specimens were cut was in most cases more than 4000 mm.

The most important visual grading parameters for the SKA data are knots, knot clusters, and growth ring width. The knots' position was determined with an accuracy of 1 mm. Knots smaller than 5 mm were not recorded. For the bending tests, the knots were only analyzed in the section between or close to the loading points, whereas for the tension tests, the knots were analyzed

Table 2 Summary of the available data.

Data	Bending	Tension	Total
Number of specimens	5773	7064	12 837
Only tKAR data available	2719	2477	5196
tKAR and SKA data available	3054	4587	7641

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between the grips. Visual grading for the analysis of geographical origin has been performed based on the tKAR value, as SKA data were not available for all specimens (Table 2). The tKAR is defined as the knot area within 150 mm projected on the end grain divided by the area of the cross section (BS 4978). Overlapping knot areas are counted only once. Table 3 summarizes the available data and gives the mean values and coefficients of variation (*cov*) for strength, MoE, density, and tKAR (CE=Central Europe, EE=Eastern Europe). Values for strength are always rounded to one decimal place; for density values, no decimal places are presented. The MoE data are rounded to the nearest hundred. Although mean values and *cov* are presented for the ungraded data set, these figures are not given for the grading results to keep the tables clear. However, the variation within one grade is a quality feature of the material and is briefly addressed when appropriate.

It is necessary to differentiate between SKA and tKAR-only data sets. For pieces with SKA data, more grading rules have been considered. For the tKAR data set, thresholds have been defined for different grades based on the visual grading standards DIN 4074-1 and BS 4978. For these standards, many geographical sources are listed in EN 1912. The 5th percentile values of the strength and density are determined nonparametrically in accordance with EN 384; for MoE, the mean is determined. Specimens tested in edgewise bending and tension were considered for the analysis, although assignments in EN 1912 are based on bending strength only. Tension test results are compared with those given in EN 338, which in turn are based on bending strength multiplied by the factor 0.6, which is expected to be on the safe side.

The available SKA data are separated for thickness of pieces to check the influence of the dimensions on the grading results for the DIN and BS standards. The thickness was favored over the width or the cross-sectional area of the specimens because it has the strongest influence on the grading of joists according to DIN rules. The frequency of the thickness is shown in Figure 1 for pieces tested in bending and in tension. In a first step, six different categories were formed with an equal number of pieces in each group. This was done for spruce independently of the loading mode. In a second step, the results for spruce tested by bending were analyzed more precisely, forming four different thickness groups: ≤37, 38–45, 46–60, and >61 mm. The boundaries were chosen to cover the important size of 38–45 mm for timber frame and 46–60 and >61 mm for typical roof structures in CE. For these pieces, the resulting strength in the different classes was analyzed additionally.

The following grading standards have been applied based on SKA data: DIN 4074-1, BS 4978, INSTA 142, NF B 52-001-1, and SIA 265. DIN 4074-1 includes different sets of grading rules for the German designations "Kantholz" (joists), "Brett/Bohle" (boards), and "Latten" (battens). The joist grading is used for all pieces loaded in edgewise bending. Both grading rules for joists and boards have been applied, depending on the sizes and cross-section shape (DIN 4074-1). Unless the boards are for glulam production, edge knots have to be considered in a special way. This optional criterion, called in German "Schmalseitenast", has been applied as well.

Differences between grading rules are partly due to the parameters of knot measurements, which can be done by determining the minimum knot diameter, the knot projected on the end grain of the board, or the knot size measured parallel to the edge of the board. Not only single knots but also knot clusters are considered in all of the standards. The length of the board over which the single knots are added up to a knot cluster is, for some standards, equal to the width of the board, whereas other standards consider a common length of 150 mm. Additional parameters are growth ring width, compression wood, and the appearance of a pith when such parameters are specified as grade-determining features in the respective standards. Some of these parameters have to be taken into account only for certain species or sizes.

The SIA rules allow for different measuring principles for grading of boards or joists. Our analysis is limited to the grading of joists. The INSTA rules depend on the shape of the cross section. Timber with thicknesses between 25 and 45 mm and a width between 50 and 75 mm has not been considered. This lowers the number of available pieces for INSTA analysis, but 6921 pieces were still available. The French standard NF B 52-001 refers to EN 1310 for the measurement of features. The NF itself considers different thresholds depending on the species. Only spruce and pine will be analyzed. For both standards, the definitions of knot types are not unambiguous and leave some room for interpretation. The standards were discussed with grading experts from the respective countries and applied to the best of our knowledge.

The differences between grading standards are not only caused by different ways of determining knot sizes but also because the number of classes vary. Where BS has two classes, INSTA and NF have four, not counting the reject. This fact influences the assignment of visual grades to strength classes in EN 338 as given in EN 1912.

The strength classes that correspond to the visual grades for the main softwood species spruce, fir, and pine are listed in Table 4. For a better overview, minor differences for single species are not differentiated in this table. The SIA classes are not included in EN 1912, but corresponding strength classes are given directly in the SIA. The grade allocation given in Table 4 is only valid for a specified source area. DIN and BS are valid for timber from CNE, INSTA for Northern Europe and Northeastern Europe, and NF for France (FR) only. SIA does not specify a certain area for which its grading rules can be applied.

In the first instance, C classes were mainly in focus. Later, the actual strength class assignments are given for all grades, species, and loading modes according to EN 1912 or national standards. For some species or loading modes, there are no assignments. In this case, the assignments are linked to the grades given in Table 4.

More data are available if only tKAR values are used. These require the derivation of fixed threshold values (tKAR) because, other than for national grading rules, there are no grades based on tKAR only. The thresholds are derived for DIN and BS. The yield was matched for both grading options based on the SKA data set. As an example, SKA and tKAR data are available for 2447 pieces graded according to DIN (joists). For the DIN grading into S13, a maximum knot value of 0.2 is allowed. In addition, other parameters also need to be considered during grading. If DIN grading results in a yield of 18%, an appropriate KAR value is chosen, leading approximately to the same yield.

The grading results from the tKAR data set are analyzed with special respect to the geographical source of the timber, as specimens from many regions were available with tKAR values. The cross section itself, which may be relevant, is not considered during this step. This seems acceptable because both DIN and BS do not have restrictions for the cross sections. For this part of the analysis, the focus is on spruce and pine tested in bending. For timber loaded in tension, single aspects are highlighted.

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Table 3 Mean values and coefficient of variation (*cov*) for bending or tension strength ($f_{m,t}$), modulus of elasticity (E_0), density (ρ), and tKAR given for different testing modes, species, and sources.

Load mode and species	Source	Total *n*	SKA	Mean values and *cov*[a]			
				$f_{m/t}$ (MPa)	E_0 (MPa)	ρ (kg m^{-3})	tKAR (-)
Bending							
Pine	PL	219	0	39.0	12 500	515	0.26
				0.42	*0.28*	*0.10*	*0.59*
	SE	209	0	45.1	11 300	481	0.21
				0.34	*0.24*	*0.09*	*0.47*
Sitka	UK	607	607	29.6	7900	404	0.37
				0.31	*0.29*	*0.10*	*0.35*
Spruce	CE	1880	1880	39.1	11 500	438	0.27
				0.33	*0.26*	*0.12*	*0.42*
	EE	840	0	35.7	10 000	396	0.30
				0.31	*0.24*	*0.10*	*0.35*
	FR	115	0	42.8	11 800	440	0.22
				0.26	*0.20*	*0.10*	*0.40*
	PL	433	432	38.5	11 400	434	0.32
				0.31	*0.25*	*0.11*	*0.32*
	SE	345	135	42.5	11 800	450	0.26
				0.36	*0.26*	*0.13*	*0.42*
	SI	1125	0	43.7	12 000	445	0.25
				0.30	*0.24*	*0.10*	*0.40*
Tension							
Douglas	CE	324	324	24.8	10 900	493	0.36
				0.50	*0.25*	*0.11*	*0.33*
Larch	CE	326	326	26.8	10 400	540	0.31
				0.47	*0.27*	*0.11*	*0.39*
Pine	CE	264	264	25.3	10 400	525	0.31
				0.42	*0.25*	*0.12*	*0.39*
	FI	257	0	31.7	11 400	492	0.25
				0.39	*0.20*	*0.11*	*0.41*
	FR	239	0	20.3	9000	512	0.32
				0.41	*0.25*	*0.09*	*0.37*
	PL	456	455	28.6	11 300	529	0.26
				0.44	*0.26*	*0.11*	*0.53*
	RU	171	0	20.4	9600	442	0.33
				0.43	*0.22*	*0.10*	*0.34*
	SE	206	0	29.7	10 400	485	0.24
				0.39	*0.22*	*0.09*	*0.41*
Spruce	CE	2895	2895	30.4	11 500	448	0.28
				0.40	*0.23*	*0.11*	*0.40*
	CH	442	0	25.1	10 900	439	0.28
				0.45	*0.24*	*0.12*	*0.41*
	EE	844	0	26.2	10 300	395	0.30
				0.42	*0.21*	*0.10*	*0.34*
	LV	106	106	30.4	11 700	466	0.33
				0.38	*0.24*	*0.11*	*0.37*
	PL	219	217	28.5	11 600	446	0.30
				0.37	*0.23*	*0.12*	*0.38*
	SE	211	0	27.4	10 100	415	0.24
				0.38	*0.23*	*0.12*	*0.46*
	SI	104	0	34.0	12 300	442	0.25
				0.44	*0.22*	*0.09*	*0.43*

[a]*cov* values are in italics.

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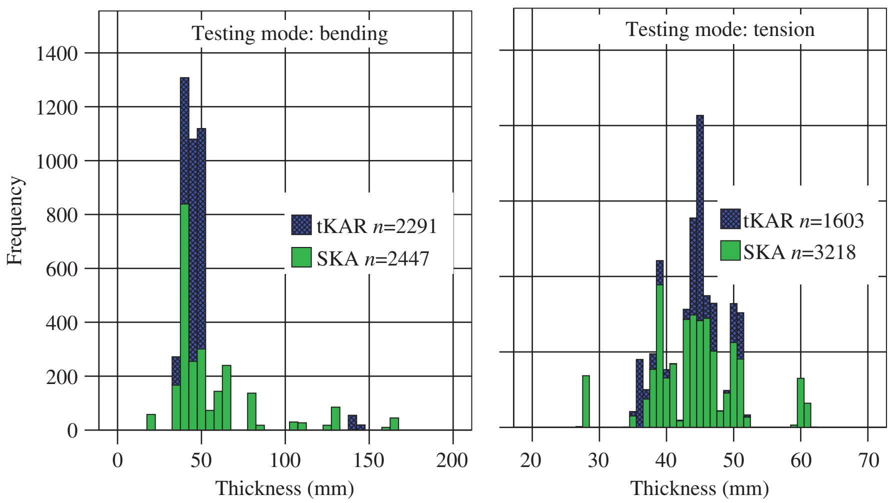

Figure 1 Frequency distribution for thickness divided by bending and tension, showing the available knot data.

Results and discussion

Cross-section analysis

Figure 2 shows the influence of the thickness for the most important grading parameters of DIN (DEK value) and BS (tKAR value). Based on the increasing R^2 values, it is obvious that with higher thicknesses, the results from knot measurement rules slowly converge, even though the correlation remains low. This means that single pieces graded according to BS and DIN will be more likely assigned to the same strength class for high thicknesses rather than for small thicknesses. At higher thicknesses, very large knot values are not detectable by any of the standards.

The influence of the cross sections on the strength was tested, and in Figure 3, the thicknesses are grouped again and plotted against the strength, focusing on the main DIN and BS grading parameter. The quality of strength prediction is higher for BS. Both DEK and tKAR promise higher strength prediction accuracy for small thicknesses. The grade-determining properties are not only based on the knot values presented in Figure 3. The results obtained under consideration of other grade-determining properties are presented in Table 5. All MoE and density values in Table 5 meet the requirements. The strength values are slightly below or above the required strength values for thickness classes of 38–45 mm and 46–60 mm. The worst case within these two groups results from 384 pieces graded into C24. The characteristic strength reaches a value of 21.9 MPa or 10% below the required value. The strength values for the largest and smallest thickness class are too low for several

Table 4 Strength class requirements for characteristic values of bending strength ($f_{m,k}$), modulus of elasticity ($E_{0,mean}$), and density (ρ_k) according to EN 338 and corresponding visual grades as given in EN 1912 for main softwood species.

EN 338	$f_{m,k}$ (MPa)	$E_{0,mean}$ (MPa)	ρ_k (kg m^{-3})	DIN	BS	INSTA	NF	SIA
C35	35.0	13 000	400	–	–	–	–	–
C30	30.0	12 000	380	S13	–	T3	ST1	–
C27	27.0	11 500	370	–	–	–	–	–
C24	24.0	11 000	350	S10	SS	T2	ST2	FKI and FKII
C20	20.0	9500	330	–	–	–	–	FKIII
C18	18.0	9000	320	S7	–	T1	ST3	–
C16	16.0	8000	310	–	GS	–	–	–
C14	14.0	7000	290	–	–	T0	ST4	–

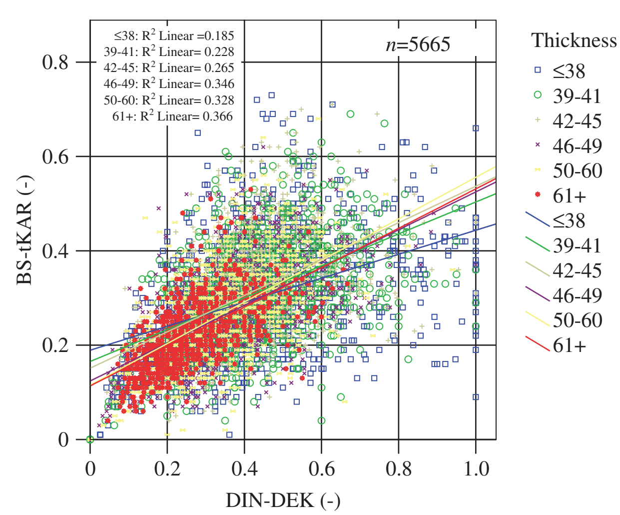

Figure 2 Important grading parameters tKAR (BS) and DEK (DIN) influenced by the thickness.

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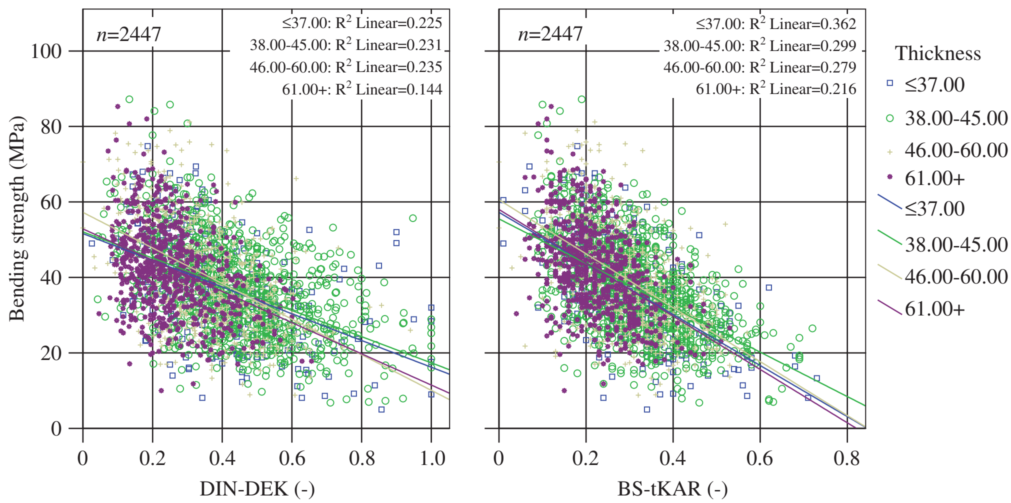

Figure 3 Scatter of knot values and quality of strength prediction for DIN and tKAR separated for thickness – for spruce tested in bending.

grades. The class 60+ shows the lowest values for the *cov* of the bending strength in strength classes C30 and C24, independently of the standard.

This is in-line with a lower variation of the ungraded material. However, the low variation of the graded material does not guarantee high characteristic strength values, because for the 60+ class, 164 pieces are graded into C30, reaching a characteristic bending strength of merely 26.9 MPa. Grading results for large and small thicknesses often do not fulfill the requirements. For large thicknesses, this is related to the knots, usually not reaching values of above 0.5 (DEK and tKAR) as can be seen in Figure 3. Downgrading of boards into C24 mainly based on relative knot sizes is apparently not accurate enough. However, for BS, the strength values for C24 are high, compared with the 38–45-mm and 46–60-mm thickness classes, as the larger cross sections seem to lead to a homogenization of the material. Trying to assign higher classes than C24 according to BS rules would also cause problems, as the current grade may not fulfill the C24 requirements anymore. Considering absolute knot sizes like in EN 1310 could help to obtain higher strength values for larger timber dimensions. Actually, NF, which is based on EN 1310, reaches the required values for larger thicknesses,

Table 5 Grading results for different cross sections – for spruce tested in bending.

Thickness (mm)	Strength class	Grading rule	n	$f_{m,k}$ (MPa)	$E_{0,mean}$ (MPa)	ρ_k (kg m^{-3})
≤37	C30	DIN	28	26.3	15 200	387
	C24	BS	111	28.4	14 300	387
	C24	DIN	94	17.1	13 200	364
	C18	DIN	65	17.0	10 700	347
	C16	BS	49	14.7	11 100	350
38–45	C30	DIN	42	31.4	14 300	403
	C24	BS	454	24.7	12 600	371
	C24	DIN	384	21.9	12 100	366
	C18	DIN	386	19.2	10 700	368
	C16	BS	232	19.5	11 000	372
46–60	C30	DIN	53	35.9	14 900	398
	C24	BS	341	24.6	12 900	357
	C24	DIN	310	23.1	12 200	357
	C18	DIN	178	19.4	10 500	354
	C16	BS	120	18.9	10 500	352
61+	C30	DIN	164	26.9	12 100	382
	C24	BS	597	26.1	12 000	377
	C24	DIN	437	24.5	11 800	366
	C18	DIN	68	21.3	10 700	356
	C16	BS	56	18.2	9700	338

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but unfortunately, in this case, the yields are very low. For strength classes above C24, the size of the specimens should be a limitation for all used standards. Disregarding the cross section for the allocation of national grades to C classes is not justified.

Grading standard

The influence of different grading standards was analyzed using SKA. There are bending data available for spruce and Sitka spruce and tension test data for spruce, pine, Douglas fir, and larch. In Table 6, the grading results are sorted by grading rules. In the following, the single grading rules are pointed out.

BS

Grading according to BS results in characteristic values above the requirements for all species, loading modes, and grades. Therefore, the assignments can be considered safe. The main reason for this is that C24 is the highest possible grade. If the rules are applied correctly, reject rates are high. They vary between 20% for spruce up and 51% for Douglas fir. Due to the sophisticated and rather complicated measuring method, it is questionable if these high reject rates are actually reached in practice.

DIN-B

As no assignment is given in EN 1912 for grading according to the DIN rules for boards, visual classes listed are based on the rules for joists. The results are higher than the requirements for spruce and pine tested in tension. For other possible combinations of species and load mode, the strength requirements are not fulfilled in several cases. The suggested strength classes for Sitka spruce are too high. Grading spruce joists according to board rules leads to the following results: the target value for C24 is clearly missed because only 20.7 MPa is reached. For spruce C30, a characteristic strength of 28.2 MPa is reached; for C18, 20.0 MPa. However, with 20.7 MPa, the strength for C24 is too low.

DIN-K

Strength values for Sitka spruce, larch, and Douglas fir do not meet the requirements for the listed strength classes. Also, for spruce tested in bending, the strength requirements are shortly missed. The results of tension tests for spruce and pine are safe.

Looking more closely at the grading of Sitka spruce, strength classes used in BS would give satisfactory results. For DIN-K, this would mean assigning S10 and higher to strength class C18. For Sitka spruce, one should focus on MoE because this is usually the grade-restricting property. Having 225 pieces in one grade would result in a MoE value of 8900 MPa. The yields resulting from DIN are higher compared with yields from BS. This is not only true for Sitka spruce, where the reject is lower by 5%, but also for spruce tested in bending, where the reject is only half that of BS. The yields for C24 and higher are comparable.

INSTA

For spruce and pine, the reached strength values are above or close to the requirements. Generally speaking, INSTA seems to work well for pine and spruce from CE. Douglas and larch show strength values below the requirements in single classes. For Sitka spruce, most strength requirements are not fulfilled. Depending on the combination of loading mode and species, the reject rates vary between 5% and 16%. Application of the additional strength class C14 leads to a lower total reject rate. No other standard gives a lower reject rate. However, this does not mean that the yields in higher classes are especially high. Unlike BS, INSTA assigns Sitka spruce to the strength classes C24, C18, and C14. As the source given in EN 1912 for INSTA is not the UK, but Norway and Denmark, the possible higher quality of Sitka spruce from these countries could be the reason for these different results. Classes above C20 can definitely not be reached for Sitka spruce from the UK.

NF

The required characteristic values are achieved except for the strength values of C30 and C24 for spruce tested in bending and for C30 of pine (n=16 only). The yield in C30 is low, whereas yields in C24 and C18 are comparable. The application of absolute knot values as grading criterion is unique among the analyzed standards. This is also an important reason why the yields in C30 are low compared with the other standards. The effectiveness of this method cannot be demonstrated by the resulting characteristic values. The bending strength for C24 is 20.5 MPa, whereas 21.1 MPa is obtained for C18. Hence, this standard does not seem applicable for grading CE spruce or pine.

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Table 6 Grading results for different grading rules.

Rule	Load mode	Species	Strength class	n	$f_{m/t,k}$ (MPa)	$E_{0,mean}$ (MPa)	ρ_k (kg m^{-3})	Yield (%)
BS	Bending	Spruce	C24	1503	25.6	12 600	373	61
			C16	457	18.9	10 700	361	19
		Sitka	C18	179	22.4	9400	347	30
			C14	178	17.5	7900	340	29
	Tension	Spruce	C24	1848	18.5	12 500	376	57
			C16	662	13.8	10 700	365	21
		Pine	C24	397	16.9	12 300	453	55
			C18	155	10.2	9800	422	22
		Douglas	C18	92	16.3	12 700	434	28
			C14	68	11.0	11 100	425	21
		Larch	C24	147	15.6	11 500	451	45
			C16	68	11.8	10 500	439	21
DIN-B	Bending	Spruce	C30	297	28.2	14 200	395	12
			C24	1012	20.7	11 900	364	41
			C18	986	20.0	11 000	363	40
		Sitka	C30	18	27.1	10 900	361	3
			C24	160	21.4	9200	355	26
			C16	188	16.6	8300	350	31
	Tension	Spruce	C30	484	22.6	13 600	393	15
			C24	1326	15.4	11 700	368	41
			C18	1152	13.6	10 900	368	36
		Pine	C30	113	28.2	14 100	503	16
			C24	271	13.8	11 200	434	38
			C18	252	11.0	10 200	435	35
		Douglas	C35	43	17.7	13 700	444	13
			C24	151	11.7	11 000	427	47
			C16	113	8.5	10 000	419	35
		Larch	C30	42	22.7	12 400	478	13
			C24	145	12.3	10 800	457	45
			C16	123	8.0	9500	449	38
DIN-K	Bending	Spruce	C30	287	28.7	13 200	387	12
			C24	1225	22.8	12 100	363	50
			C18	697	19.1	10 700	361	28
		Sitka	C30	6	37.3	11 100	392	1
			C24	219	20.0	8800	349	36
			C16	169	17.8	8400	354	28
	Tension	Spruce	C30	267	21.9	14 000	397	8
			C24	1541	17.2	12 000	369	48
			C18	1082	13.4	10 700	369	34
		Pine	C30	91	26.6	13 900	483	13
			C24	303	14.9	11 800	448	42
			C18	225	10.4	9600	417	31
		Douglas	C35	27	17.8	13 300	441	8
			C24	69	14.1	12 100	434	21
			C16	117	12.9	10 700	424	36
		Larch	C30	22	17.4	13 300	485	7
			C24	138	13.8	11 100	451	42
			C16	87	8.2	9800	446	27
INSTA	Bending	Spruce	C30	396	28.5	13 500	389	18
			C24	619	25.6	12 500	366	27
			C18	928	20.0	10 900	359	41
			C14	210	12.8	9700	360	9
		Sitka	C24	52	16.1	8500	351	9
			C24	127	19.7	8900	345	21
			C18	239	15.1	7900	337	39
			C14	95	15.3	6800	345	16

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(**Table 6** Continued)

Rule	Load mode	Species	Strength class	n	$f_{m/t,k}$ (MPa)	$E_{0,mean}$ (MPa)	ρ_k (kg m^{-3})	Yield (%)
INSTA	Tension	Spruce	C30	371	21.8	13 600	382	13
			C24	760	19.2	12 400	369	27
			C18	1197	15.1	11 100	366	43
			C14	327	11.3	9900	365	12
		Pine	C30	98	25.7	13 800	499	16
			C24	129	18.2	12 400	450	22
			C18	231	11.9	10 500	415	39
			C14	89	8.8	9200	429	15
		Douglas	C30	17	17.6	13 900	467	5
			C24	35	10.6	13 000	435	11
			C18	132	13.4	11 000	426	41
			C14	88	9.5	9900	416	27
		Larch	C30	36	16.8	12 700	471	11
			C24	62	16.6	11 600	452	19
			C18	126	8.6	9900	442	39
			C14	59	11.9	9700	461	18
NF	Bending	Spruce	C30	52	28.1	14 300	373	2
			C24	763	20.5	12 400	371	31
			C18	897	21.1	11 500	359	37
	Tension	Spruce	C30	178	24.4	14 000	406	6
			C24	1167	17.0	12 000	371	36
			C18	1065	14.7	11 300	364	33
		Pine	C30	16	12.0	13 200	499	2
			C24	158	20.0	13 100	471	22
			C18	200	12.7	10 800	434	28
			C14	257	10.2	10 100	431	36
SIA	Bending	Spruce	C24	100	30.5	14 300	409	4
			C24	369	23.8	12 800	377	15
			C20	390	22.8	12 100	366	16
		Sitka	C24	5	39.1	10 700	409	1
			C24	39	22.1	9400	331	6
			C20	62	17.9	9000	332	10
	Tension	Spruce	C24	180	23.1	14 300	412	6
			C24	272	17.7	12 800	371	9
			C20	379	18.0	12 300	372	12
		Pine	C24	67	25.5	14 000	487	9
			C24	62	19.4	12 600	480	9
			C20	91	14.5	11 500	450	13
		Larch	C24	14	27.4	13 700	498	4
			C24	40	15.8	12 000	472	12
			C20	39	8.0	10 600	431	12
		Douglas	C24	15	17.6	15 000	465	5
			C24	34	16.0	12 900	436	11
			C20	18	11.5	11 700	441	6

SIA

For SIA, no strength classes higher than C24 are listed in the national standard. The two national classes, FK1 and FK2, are both assigned to strength class C24. Characteristic values are usually kept, whereas reject values are extremely high. Knots in the SIA are measured at right angles to the length of the pieces, which is comparable to most other grading standards, but very restrictive threshold values lead to high reject rates. A value of 1:3 for the ratio of the single knot to the width results in the rejection of a piece. According to the INSTA rules, single knots of that size are still allowed for the grade C30. The practical use of the SIA standard with reject rates between 65% and 83% does not seem possible.

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Comparing the *cov* values for species, the lowest *cov* of in-grade timber can be found for spruce tested in bending, independent of the used standard. DIN and BS show similar results across all strength classes (*cov* 0.27–0.30), but INSTA rules lead to lower *cov* values. NF shows the highest *cov* values except for the highest strength class C30 (*cov* 0.24). Independent of the standard, none of the grades shows a *cov* <0.24. Highest *cov* values are found for Douglas fir.

Source

The influence of the geographical source threshold values was analyzed only by tKAR. These data are determined in such a way that approximately the same yield is obtained as in DIN or BS. For the DIN grading, the single-knot value DEK is plotted against the tKAR (Figure 4). This means for DIN that those pieces with tKAR values equal or lower than 0.16 are assigned to strength class C30. Of course, the pieces in this grade differ from those assigned to C30 (S13) by the exact DIN grading. For the BS, the difference is smaller because the main grading parameter is the tKAR value. However, BS also specifies a margin KAR value as a second important grading parameter. This value is based on knot measurements close to the edges of the pieces. To achieve a comparable yield, a number of margin KAR specimens are exchanged with tKAR specimens. Figure 4 makes the difference between DIN and BS rules obvious.

The consideration of the highest visual grades in both cases leads to the following results: for DIN, the new C30 grade (tKAR grading) consists of pieces originally graded into all possible DIN grades (SKA grading). S13 accounts for a maximum of 50% in the tKAR C30 grade. The BS pieces that are now assigned to C24 mainly originate from the SS grade. Only a small number of pieces originally graded into GS grade are added, where a margin KAR above 0.5 is combined with a tKAR between 0.2 and 0.29.

The determined tKAR threshold values are given in Table 7. The influence of the testing mode or the species is small. For C24, the tKAR value is always 0.29, except for DIN grading, where this value is slightly higher (0.30). The differences reach a maximum for grading into C30 according to DIN yields. Values vary between 0.13 and 0.16 in this case. As these values are close together, the following grading procedure is based only on the tKAR values for spruce tested in bending, and the results are considered representative for grading according to the standard.

Table 8 contains the grading results for bending. As shown at the top of Table 8, the characteristic values for data from CE are lower, compared with the SKA grading, which includes timber from Poland (PL) and SE (Table 6). The calculated total tKAR value of 0.16 for C30 leads to a characteristic bending strength of 28.0 MPa instead of 29.1 MPa. This is acceptable, as only tKAR was used and the results are based on the equivalence of yield in the different grades. However, these grading results have to be judged carefully, especially for the DIN-based results. The relative yield in the larger data set is slightly higher if only tKAR is used for grading. Throughout all grades, the characteristic values for BS are closer to the required values. This might be due to the fact that there is no grade for grading timber into C30, and therefore, the better material is not graded into C30 but to C24 instead. On the contrary, one might also argue that in case of a higher grade, the grade boundaries for C24 (SS grade) would need some adjustment.

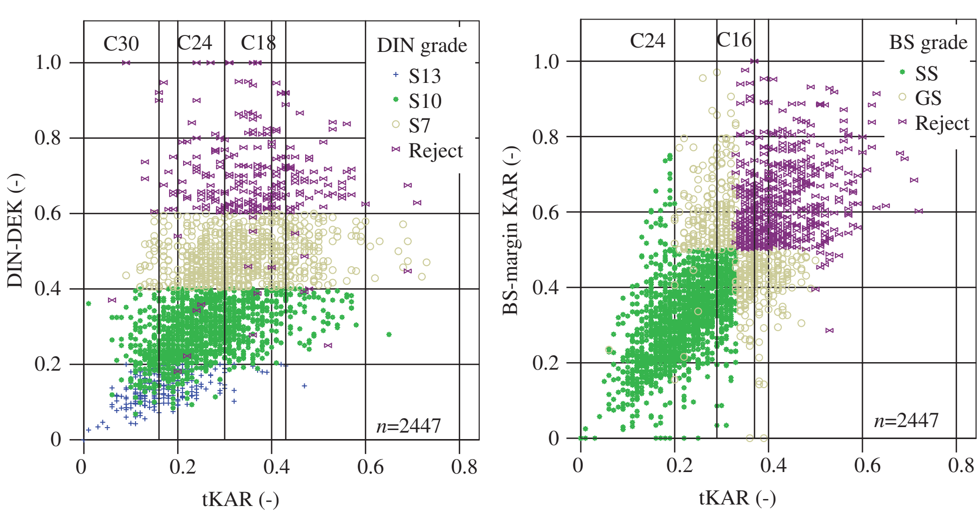

Figure 4 Illustration of the derivation of threshold values used for the grading of different sources for spruce tested in edgewise bending.

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Table 7 tKAR values that give a comparable yield to the grading standards DIN or BS respectively.

	Spruce bending		Spruce tension		Pine tension	
	DIN	BS	DIN	BS	DIN	BS
C30	0.16	–	0.14	–	0.13	–
C24	0.30	0.29	0.29	0.29	0.29	0.29
C18	0.43	–	0.42	–	0.41	–
C16	–	0.36	–	0.36	–	0.37

Eastern Europe

Independent of the grading procedure, the obtained strength values are close to the required ones. A considerable reduction in yield compared with CE can be observed due to the low quality of the ungraded material (Table 3). Forty-five percent of the pieces do not reach strength class C24 or higher for DIN grading, but the assignment seems to be correct. In addition, the variation of strength values within the strength classes is small. Only timber from SI shows *cov* values within that range (0.22–0.29). Density values are well below the requirements as for the tKAR grading, but no parameter is available for predicting the density (growth ring width). The requirement for C30 is 380 kg m^{-3}, and only 336 kg m^{-3} is achieved. Looking at the characteristic values independent of the grade, it is questionable whether the growth ring width is sufficient to predict density, which is good enough and reaches the density requirements for C24 or higher.

France

The data set from FR is too small for reliable statements with regard to the applicability of either DIN or BS standard.

Poland

For all classes and grading standards, the strength values for pine are too low. This cannot be explained by low strength values for the ungraded material, as the mean value is in the range of ungraded spruce data. In addition, the variation within the strength classes reaches a maximum compared with other countries (*cov* 0.31–0.38). The MoE and density values are met. Visual grading of pine from PL does not work when applying DIN or BS standards.

For spruce, except for the bending strength for class C30, which is only based on the minimum value of 25 pieces, the characteristic values are met. This does not indicate a high quality raw material. The values required for C24 are met, both for DIN and BS.

Sweden

For SE pine, yields are at least as high as for pine from PL, although the characteristic values are met. For spruce, the characteristic values are close to the requirements, except for C30, where 63 pieces out of 345 in this grade have a characteristic strength value of only 24.5 MPa.

Slovenia

Timber from Slovenia shows extraordinary good strength values for the timber properties in the ungraded data set (Table 3), and consequently, good grading results with low reject rates could be obtained. Graded based on the threshold values of DIN, the reject rate is as low as 3%. If the ungraded spruce material shows values that are constantly moving in the upper range of possible strength, MoE, and density distributions, the choice of the grading standard should be done by focussing on the yield only, as the grading results will always be safe.

The grading output for tension is presented without precise listing of the results in a table, and only single aspects are highlighted in the following.

Tension data (all sources)

Pine tension data are available from Finland (FI), FR, Russia (RU), and SE. Table 3 shows that there are already considerable differences in strength properties for the ungraded timber sources. These differences are reflected in the grading results. For timber from FI and SE, the required values are reached. Although the yields are close together, FI timber shows tensile strength values far above the requirements (26.8 MPa for C30, n=54/17.9 MPa for C24-DIN, n=123).

Timber from FR and RU clearly shows lower values for the ungraded samples (see Table 3) compared with timber from FI and SE. The tKAR grading leads to similar yields for timber from RU and FR. However, there is a difference in terms of obtained characteristic strength values. Grading FR timber into C24-BS leads to a characteristic strength of 8.9 MPa (n=105), where 14.4 MPa

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Table 8 Grading results for different sources (bending only).

Source	Species	Strength class	Visual standard	*n*	$f_{m,k}$ (MPa)	$E_{0\ mean}$ (MPa)	ρ_k (kg m^{-3})	Yield (%)
CE	Spruce	C30	DIN	315	28.0	13 400	390	17
		C24	BS	1186	24.8	12 500	374	63
		C24	DIN	931	23.8	12 100	367	50
		C18	DIN	471	17.2	10 300	358	25
		C16	BS	337	18.9	10 700	359	18
EE	Spruce	C30	DIN	73	28.5	11 500	336	9
		C24	BS	424	23.6	11 000	340	51
		C24	DIN	384	23.2	10 800	342	46
		C18	DIN	289	18.0	9200	336	34
		C16	BS	200	20.0	9600	336	24
FR	Spruce	C30	DIN	31	25.1	12 200	379	27
		C24	BS	94	26.5	12 000	381	82
		C24	DIN	68	25.4	11 800	375	59
		C18	DIN	14	16.5	11 200	376	12
		C16	BS	15	23.3	11 300	375	13
PL	Pine	C30	DIN	69	19.9	14 400	452	32
		C24	BS	134	21.2	13 900	441	61
		C24	DIN	70	21.5	13 200	434	32
		C18	DIN	49	13.1	11 000	435	22
		C16	BS	39	13.4	11 200	434	18
	Spruce	C30	DIN	25	19.1	14 600	411	6
		C24	BS	194	24.7	12 800	373	45
		C24	DIN	188	24.4	12 500	372	43
		C18	DIN	169	19.9	10 500	356	39
		C16	BS	106	19.9	11 100	356	25
SE	Pine	C30	DIN	73	30.1	13 000	439	35
		C24	BS	165	26.5	11 700	420	79
		C24	DIN	99	24.9	10 700	412	47
		C18	DIN	34	15.3	9500	403	16
		C16	BS	31	15.1	9800	407	15
	Spruce	C30	DIN	63	24.5	12 700	370	18
		C24	BS	231	23.7	12 200	360	67
		C24	DIN	177	23.2	12 000	355	51
		C18	DIN	74	15.2	11 400	346	21
		C16	BS	58	13.8	11 800	345	17
SI	Spruce	C30	DIN	231	34.8	13 800	388	21
		C24	BS	798	27.4	12 600	383	71
		C24	DIN	602	25.2	12 000	379	54
		C18	DIN	246	20.4	10 600	363	22
		C16	BS	194	21.1	10 800	367	17

is required. Timber from RU reaches 14.1 MPa. Because the mean knot values of the ungraded material from RU and FR are also close together for both sources, the correlation between tKAR and tension strength has been checked: for the whole data set of pine loaded in tension, an R^2=0.47 is found; for RU pine, R^2=0.46, whereas for FR pine, it is only R^2=0.18. Hence, a reliable prediction of the strength of French pine based on tKAR seems to be impossible.

For spruce tested in tension, the differences for the ungraded material are small for different sources. The values for timber from CH, EE, and SE are close together, whereas the timber from SI again shows higher strength values (Table 3). For the small data set from SI, all requirements are fulfilled. In addition, the grading results for the other sources are closer to the required values compared with the results for pine. The required strength values for C18-DIN and C16 for timber from SE are not reached. Eastern European timber fulfils the strength requirements, except for C30 (16.6 MPa), but fails the density requirements again. Timber from CH does not reach the strength requirements for C24-DIN (13.1 MPa) and C18 (9.3 MPa).

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Comparing bending and tension, it seems more likely that the required characteristic values for pieces tested in tension are met. Many deviations from the required strength values are small or can be explained. For instance, the timber from Switzerland was tested over a longer span than nine times the height, leading to lower strength values (length effect).

Conclusions

Among the three parameters, cross sections, source of the timber, and grading standard, the last is the most influential. The different rules of measuring knots and the number of grades in a standard influence the results. Moreover, an effect of the cross section and the source of the graded timber have been shown to be relevant. For example, it is not possible to grade C30 with large cross sections because of the relevance of knot sizes and dimensions for visual grading. Grading results are similar for DIN, BS, and INSTA. For sources, for which SKA data were available, the requirements are met or nearly met. Having only two grades in a standard (such as in case of BS) makes it easier to reach the required values for all possible combinations of species and type of loading. All three standards could be used for CE timber. Reject rates are lowest for INSTA, as only this standard has a grade for C14. This trend is not transferable to high grades. Yields for C24 and higher vary from 62% for grading according to DIN to 45% for grading according to INSTA (spruce, bending). For European spruce, the characteristic values are close to the required values for all three standards, with a maximum deviation of around 10% below the required value. The absolute reject rates for visual grading vary depending on several factors, such as cross section, grading standard, and/or knot definitions. In practice, these rates will be even higher because the full board length needs to be graded, whereas in this study, only the central section has been graded. The results for NF show low yields for C30. The distinction between C24 and C18 is not really sharp. This leads to equal yields and similar characteristic values for these two grades. Hence, in CE spruce, the characteristic values for C18 are met, whereas for C24, they are not. The SIA 265/1:2009 standard leads to extreme reject rates and a practical use is not possible.

Visual grading results are clearly influenced by the source of the timber. Grading into C30 seems to be especially problematic in a number of cases. Depending on species, source, and grading rules, declared growth areas need clarification for a number of standards, and growth areas cannot be extended without additional testing or changes in the grade limits. Allocations in EN 1912 for softwoods are not correct in a number of cases, and a review seems necessary. New limits for source areas and cross sections are required. This can only be done based on a review of data, where the respective grading standards have proven their applicability for the listed grade, source, and cross section.

Acknowledgments: We like to thank Olaf Strehl and Andreas Gossler of HFM for programming the grading rule routines into the database and our student assistants for measuring tens of thousands of knots.

Received March 15, 2013; accepted July 12, 2013; previously published online August 7, 2013

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