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A discussion on the introduction of wood to the JCSS probabilistic model code

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1. Introduction

The JCSS code is a probabilistic model code. This is intended to provide a complete set of models and distribution information of loads and resistances for the user to be able to make a probabilistic based assessment and design of structures. Regarding building materials, at present the JCSS model code covers concrete, reinforcing steel and steel. Wood is not included in the code at present. The purpose of this paper is to stimulate the discussion on how wood should be presented in the JCSS model code.

2. Background: A summary of existing strength data based on the Nordic Wood project on the reliability of timber structures, /Ranta-Maunus (2001)/

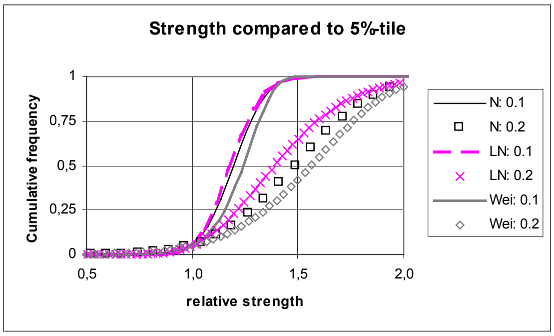
The purpose of the strength data collection and analysis was to find more information on the strength distribution, which is needed in the reliability analysis of timber structures. This part is briefly summarised below.

- Only the lower tail of strength distribution necessary

First, a sensitivity analysis revealed that the calculated reliability is sensitive to the lowest strength values, whereas the values around the mean have no effect. Therefore, in order to get correct information for reliability analysis, we need an adequate sample size, and the distribution function should fit well to the lowest values in the relevant population. Considering the test database size, a population of 1 000 test data can be considered adequate. The population can consist of a combination of different test series. Then the distribution functions can be fitted to the lower tail, e.g. 10%, of the values, and used both to determine the characteristic 5th percentile value and to estimate the structural reliability.

- The lower tails of different distribution functions are very different

As a background, the figure below shows the shape of some commonly used distribution functions pictured for the whole distribution and for the of the lower tail of the distribution. From these figures, it can be seen that at the lower tail of the log-normal distribution is very steep compared the normal distribution for instance. This of course results in higher coefficients of variation when the log-normal is used compared to the normal distribution.



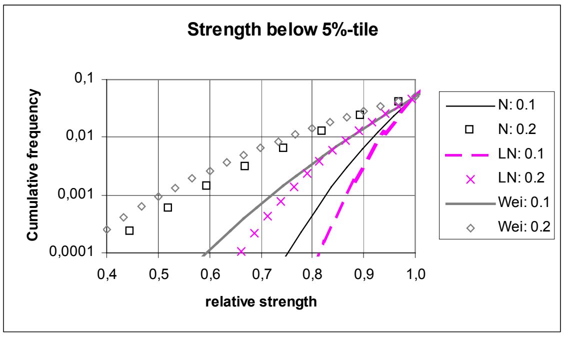


Figure 1. Comparison of Normal (N), Log-normal (LN) and 2-parametric Weibull (Wei) distributions when coefficient of variation is 10 or 20%., the number following N, LN or Wei is the coefficient of variation, Ranta-Maunus et al.(2000)

Summary of strength data

Nordic project partners have collected and analysed such existing strength data of timber materials to which they have access. We have analysed the bending data of sawn and round timber, LVL, glulam, finger joints, I-beams and plywood. The tension strength results of glulam lamellae, and compression data of round timber have also been analysed in the project. (appendix)

Only the results obtained from the largest samples are included here.

- From the sawn timber data, only machine-graded timber with a sample size N > 500 is included (with the exception of a sample of Irish-grown sitka spruce (N = 386), in order to include some results other than Scandinavian). The results of visually graded timber are not included because of the low yield of the method. The largest population of sawn timber we analysed comprised 1 300 specimens.

- From Kerto LVL we have nearly 2 000 quality control specimens both in edge-wise and flat-wise bending.

- From tension tests of glulam lammellae a sample of 1 000 specimens were available, and 600 for bending of finger joints.

- For small-diameter round timber, about 600 bending and compression test samples have been analysed.

The samples for other materials are unfortunately smaller. Since no other information was available, the following samples are also reported here: plywood (281), glulam (126 + 109), and I-beam (294). (appendix)

The strength distributions are illustrated on a relative scale in fig. 1, where all strength values are divided by the 5th percentile. For comparison, curves for log-normal distribution with COV = 10, 20 and 30% are shown as well. The upper figure with linear probability scale shows the differences above characteristic value, whereas the smallest strength values can be compared when logarithmic scale is used (lower figure).

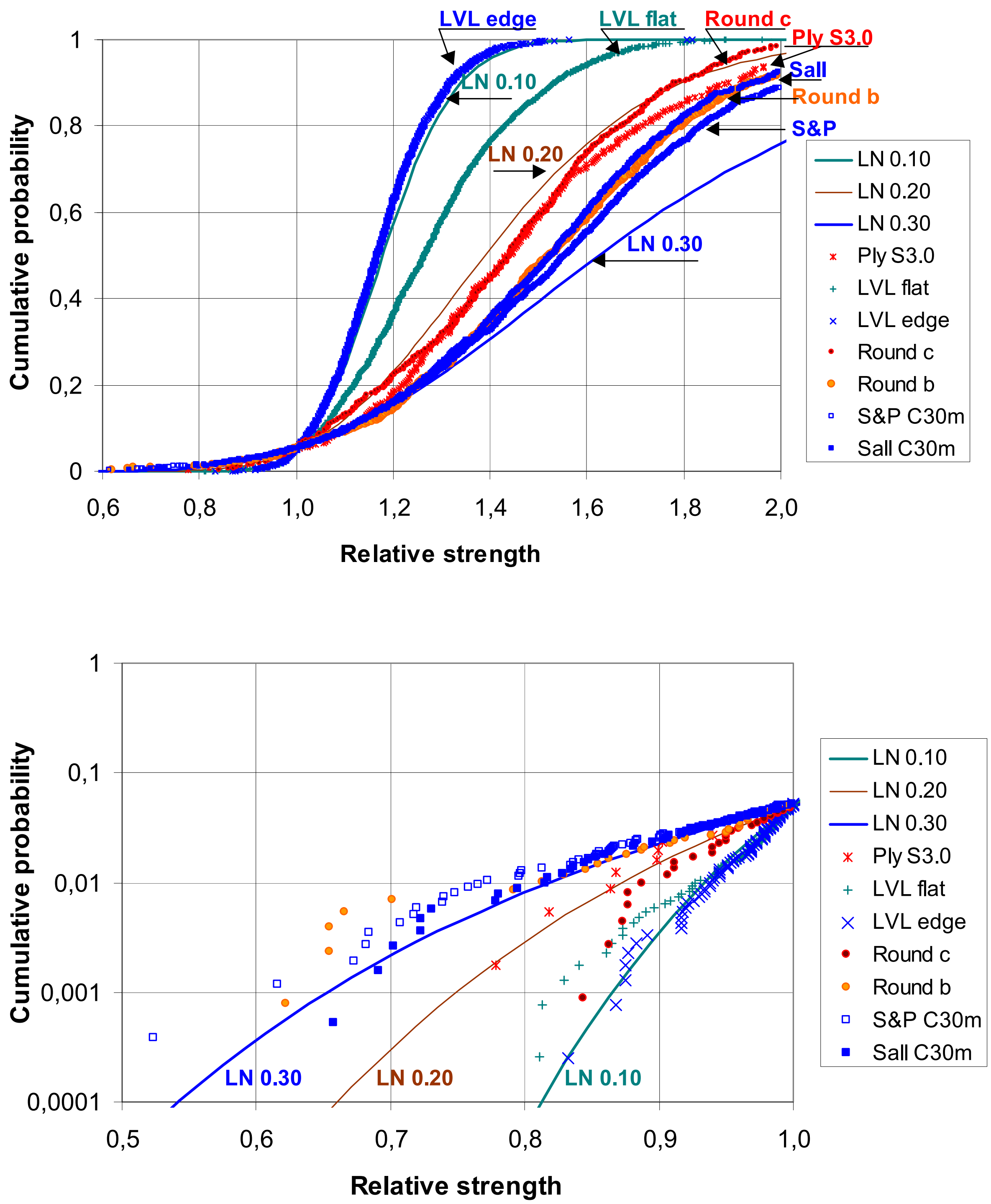


Figure 2. Cumulative probability distributions of relative strength (strength per 5th percentile) of sawn and round timber, LVL and plywood on linear and logarithmic scale as well as log-normal function with COV = 0.1, 0.2, and 0.3.

The results are reported in detail in references Ranta-Maunus et al. (2001), Sorensen and Hoffmeyer (2001) and NTI (2001). A summary is provided here concerning the parameters of distribution functions fitted to the data in terms of COV.

When strength data is used in the reliability analysis, it is essential that the distribution function used fits well with the lower strength values, otherwise the reliability values are misleading. Therefore, we fitted distribution functions separately to all the data and to the lower tail, 10 % in many cases. If both fittings gave nearly the same result, we concluded that this material follows the distribution in question, and we could use the parameters obtained from any of the fittings.

For LVL and plywood we obtained nearly the same COV when fitting log-normal distribution to all the data and to the lower tail.

On the other hand, the sawn timber results show a flatter tail than that of log-normal distribution, only a little steeper than normal distribution. When we used log-normal distribution to describe this data, we used COV based on the fitting to lower tail.

The results of analysis are shown in Tables 4 (sawn timber) and 5 (others) (in the appendix) concerning the 5 percentile value observed versus the target value of the grade, and the COV parameters of normal, log-normal and 2-parameter Weibull distributions fitted to the lower tail data. The 5^{th} percentile value is based on a non-parametric distribution, which is the method used in the EN-standards for sawn timber. In most cases, the 5^{th} percentile is close to the target value with some exceptions.

The result is contradictory for glulam: the testing made by its constituents, lamellae and finger joints, suggests that there could be a problem in the strength of glulam, whereas the strength of glulam exceeds the code value. We should obtain more data on glulam in order to be able to draw conclusions on the tail data.

Visually graded sawn timber, which is not reported here, gives normally a higher 5^{th} percentile value than needed for the grade. Therefore, this traditional method can be considered conservative but uneconomic. Another problem associated with the tests of visually graded timber is that the grading is made in the laboratory, indicating the conservatism of the grading rules rather than the high strength of commercially produced material.

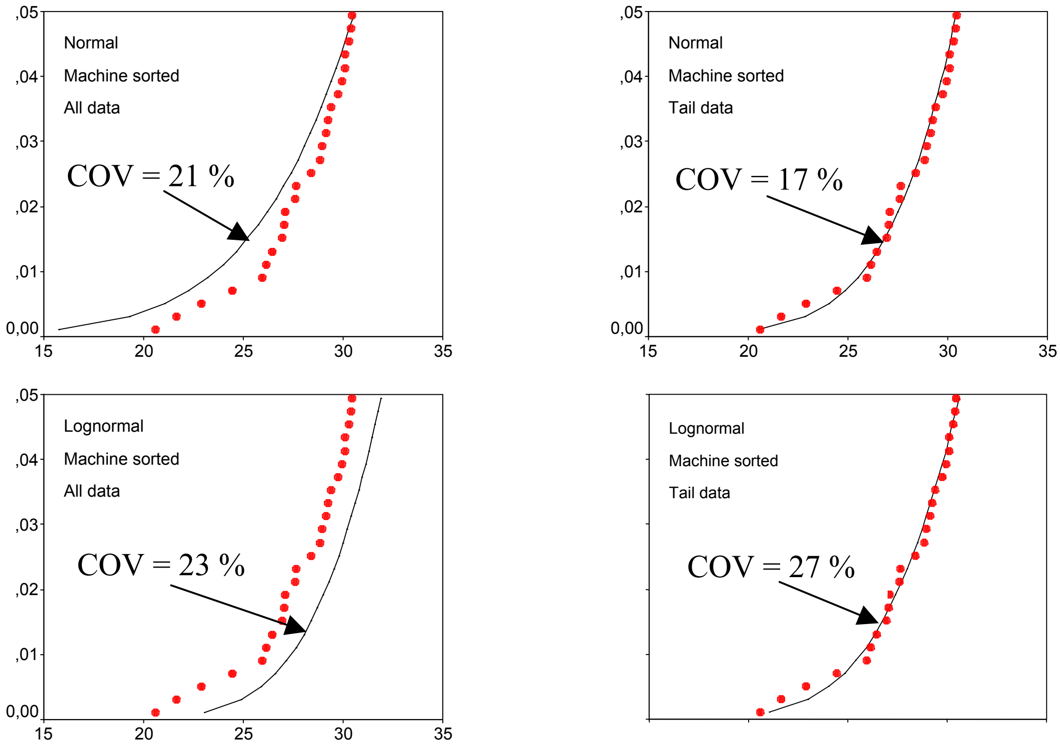


Figure 3. Cumulative distributions of bending strength for machine sorted spruce of dimensions 42 x 146 mm. The spruce was sorted by Raute Timgrader to the European strength class C30. The coefficient of variation values are given for the distributions, showing high values for the tail-fitted log-normal distribution.

3. Tail-COV

When normal, log-normal and 2-parameter Weibull distributions are fitted to the lowest 10% of the results, the COV parameters related to these functions are quite different, as shown in Tables 1 and 2. Sawn timber, which has COV of the whole test data from 21 to 29 %, has the COV parameters of tail-fitted distributions as follows:

Normal distribution: 18 – 24 %
Log-normal distribution 29 – 35 %
2-parameter Weibull 14 – 21 %

For the above reason, we give a new definition, namely **tail-COV** to the distribution property which is retrieved by tail-fitting the 10% lowest part of the distribution. This does not define the variation of the whole distribution, but merely expresses the shape of the lower tail can be regarded as a material parameter.

Distributions fitted to the lower tail of the tension strength of lamellae, and bending strength of finger joints and round timber have similar tail-COV parameters as sawn timber.

Engineered wood products, and round timber in compression had smaller tail-COV values.

Ungraded small-diameter round timber, which had a COV of all data of 23 %, obtained a tail-fitted COV parameter of log-normal distribution as low as 18%. In engineered products, the COV of tail-fitted log-normal distribution is close to the COV of the entire data. For LVL we obtained a tail-COV around 10%. For other EWPs the sample size should be larger so that we can draw firm conclusions on the shape of distribution tail.

4. Recommendations

Based on the analyses performed, the following recommendations are made:

The data available suggests that engineered wood products follow well the log-normal distribution, and sawn timber could be better described by normal or Weibull distribution. However, it is suggested that log-normal distribution is used for all timber materials in structural reliability analysis, because it is widely used for other materials and because it seems to be the best for timber materials used for long span structures as well.

When more specific information is unavailable, the COV parameters of log-normal distribution can be taken from Table 1. It has to be observed that the data used in this work was based on the testing of:

- mainly Nordic sawn timber
- Kerto-LVL
- Finnish 3 mm-ply spruce plywood (only 300 specimens)
- Norwegian I-beams (only 300 specimens)
- Norwegian glulam (only 100 + 100 specimens).

It would be valuable, especially for glulam, which is used in long-span structures, if a much bigger population were analysed.

Table 1. Typical values for the tail-COV parameter. The log-normal distribution is recommended when used in structural reliability analysis.

Material	COV of all strength data [%]	Tail-COV [%] normal	**Tail-COV [%] log-normal**
Machine graded sawn timber	22	20	**30**
Plywood*)	18	14	**20**
Glulam*), I-beam*)	13	11	**15**
LVL	10	8	**10**

*) inadequate population (N < 300).

5. Strength distributions

Based on the above test results the following strength distributions may be given to describe the lower tail of the distribution, Table 2. It should be noted that the same distribution is used here also for the other grades which have not actually been tested. This is done simply by shifting the distribution so that the characteristic value coincides with the 5-percentile value of the distribution.

The following assumptions are done:
- The log-normal distribution is used in all cases.
- The tail-COV is given as recommended in table 1.
- The characteristic value is placed as the 5-percentile to fix the distribution.

Table 2. Example strength distributions for some structural grades and Ewp's.

Grade	C18	C24	C30	C40 *
$f_{m,k}$ [MPa]	18	24	30	40
Distribution parameters: Log-normal N(μ_{ln}, σ_{ln}) , tail-cov = 30 [%]				
μ_{ln}	3.3373	3.6610	3.8842	4.1719
σ_{ln}	0.2936	0.2936	0.2936	0.2936

Material	LVL, flat-wise and edge-wise		Glulam GL30 (Tentative)	
$f_{m,k}$ [MPa]	50		30	
Distribution parameters: Log-normal N(μ_{ln}, σ_{ln}) tail-cov =	10 [%]		15 [%]	
μ_{ln}	4.0765		3.6466	
σ_{ln}	0.1000		0.1492	

$f_k = e^{\mu_{\ln} - 1.645\sigma_{\ln}}$; $COV = \sqrt{e^{\sigma_{\ln}^2} - 1}$

* *Paper by Ranta-Maunus (in this meeting) suggests that the tail-COV should be lower for C40*

6. The material properties needed

A base set of material properties as well as some influencing factors are needed for a probabilistic design. The properties should primarily be expressed as distributions, where the variability of the property is considered. However, the variability of many properties are not fully known and there is lack of experimental results for all properties to be expressed as distributions. These may be linked to other properties such as the bending strength to other strengths as given by EN 384. However, some consideration should be given to the spread of the distribution of the other strengths (other than bending).

Table 3. Estimated tail-COV for other strengths.

Strength of loading mode	**Expected coefficient of variation**
Bending, MS sawn timber	For nordic softwoods COV is known For other species data could be found
Bending, Glulam	Some experimental evidence available
Compression and shear, ⊥ ‖	Not known, *lower COV suspected (round wood tests)*
Tension, ⊥ ‖	Not known, *similar or higher COV suspected*
Joints	Not known, *lower COV suspected*

The material strength is the most important property considering structural capacity and this should always be expressed as a distribution. The material strength is needed for the different strength classes as well as for other major wood based products.

As for the influencing factors, such as moisture effects, load duration effects, size and system effects, it may be discussed whether to use deterministic values for such properties. This would highly simplify the task of the designer.

It is here suggested that the input to the JCSS is done in different stages as below. This is to make the use of wood in probabilistic design simple for the designer. At a second stage (stage 2) more elaborate models could be included, which would mostly be used by researchers to define the numerical values of the deterministic influencing factors of stage 1.

First level

- As a first stage the bending strength distributions are given to the codes as they are fitted to the lower tail of the test results. This is used also for the other strength grades by simply shifting the distribution as according to the prescribed 5-percentile characteristic value.

- The other strength values are made relative to the bending strength. There is a point for major discussion here:
  a) There is some evidence that for compression failures the distribution is narrower than for bending and tension. A lower value of the tail-COV could be applied for compression strengths and probably also for shear strengths
  b) Regarding timber joints (other than finger joints) there is no material at hand. It is suspected though that in the case of mechanical timber joints, the distribution of failures is narrower than for bending of structural timber.

- The influencing factors are deterministic and have values as given in Eurocode 5 (moisture effect, duration of load effect, size, system effect).

- With this information the designer is able to do a reliability analysis. All the example calculations given in the JCSS model code could be calculated as if the structures were made of wood.

Second level

- As a second stage more elaborate models could be given.

- These models should be presented in a way that they are ready for use with all the information available.

- These could be used either in reliability analysis or to determine the values of influencing factors for deterministic codes.

- Many such models seem to be emerging also in this Cost action.

Table 4. Material properties needed for the model code

	First level • Based on experiments and codes • Should be completed soon	Second level • Advanced models • Can be completed later and updated constantly
Users	• Used by structural designers • All JCSS example calculations may be readily done	• Used by researchers • Used primarily to adjust deterministic parameters
Material Strength	Based on experiments EN 408, distribution fitted to the lower tail Log-normal distribution as given in table 1	More elaborate strength models which might include: - lengthwise variation - species effects
Other strength properties	From experiments or related to bending strength as EN 384	(as above)
Correlation matrix	At least between: strength-elasticity-density	Full correlation matrix
Effect of moisture and load duration	Deterministic: k_{mod} and k_{def} as given in Eurocode 5	Models for - Damage accumulation - Creep models - Mechano-sorptive effects - Moisture induced stresses
Size effect	Deterministic: Height effect as given in Eurocode 5	Models for - Length effects - Load configuration effects - Volume effects
System effects	Deterministic: load sharing factor as given in Eurocode 5	Analysis procedures for systems

7. References

EN 384 (1995) European Standard, Structural timber – Determination of characteristic values of mechanical properties and density.

EN 408 (2002) European Standard, Timber structures – Structural and glued laminated timber – Determination of some physical and mechanical properties.

EN 1995-1-1 (2002) Eurocode 5: European Standard, Design of Timber Structures, Part 1-1: General rules and rules for buildings.

Dalsgaard Sorensen J., Hoffmeyer P., 2001, Statistical Analysis of Data for Timber Strengths. Manuscript.

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Ranta-Maunus A., Summary report of NI project on reliability of timber structures. October 2001. Joint Nordic wood project meeting and Cost E24 workshop. Copenhagen.

Ranta-Maunus A., Fonselius M., Kurkela J., Toratti T., 2001, Reliability analysis of timber structures. VTT Research Notes 2109. Espoo, Finland. 102 p + app. 3 p

Alpo Ranta-Maunus, Mikael Fonselius, Juha Kurkela, Tomi Toratti (2000) Sensitivity studies on the reliability of timber structures. CIB-W18 paper

Table 4. Collection of machine-graded sawn timber bending strength distribution data, and bending and compression data of ungraded small- diameter round timber. The type of distribution fitted to the lower tail data is given as well as the COV parameter of the fitted distribution, the tail used for fitting as % of total sample and $f_{0.05}$ based on non-parametric distribution.

Species	Origin	Grade	$f_{0.05}$ [N/mm²]	Grading method	Sample size	Tail fitted [%]	Distribution type	COV [%]	Reference
Spruce	Finland	M30	30.5	Bending	496	10	Normal Log-normal 2-P Weibull	18 29 14	Ranta-Maunus et al. 2001 S-1 in Table 2.3
Spruce	Finland	M30	31.3	Bending	986	10	Normal Log-normal 2-P Weibull	19 31 15	Ranta-Maunus et al. 2001 S-1 to S-99 in Table 2.7, “Sall” in Figure 1
Spruce and pine	Finland, Sweden	M30	30.6	Bending	1327	10	Normal Log-normal 2-P Weibull	20 35 17	Ranta-Maunus et al. 2001 Table 2.10, “S&P” in Figure 1
Spruce and pine	Sweden and Finland	M24	24.6	Dynamic	819		Normal Log-normal 2-P Weibull	24 35 21	Dalsgaard Sorensen, Hoffmeyer Table 6.11, Series F all
Sitka spruce	Ireland	M30	27.1	Bending	386	30	Normal Log-normal 2-P Weibull	23 34 21	Dalsgaard Sorensen, Hoffmeyer Table 7.2, Series H, Cook Bolinder
Small round timber, bending	Finland, UK, Austria		36.6	None	660	10	Normal Log-normal 2-P Weibull	20 34 16	Ranta-Maunus et al. 2001 Table 2.20, Spruce and pine, “Round b” in Figure 1.
Small round timber, compression	Finland, UK		17.8	None	575	10	Normal Log-normal 2-P Weibull	13 18 9	Ranta-Maunus et al. 2001 Table 2.20, spruce and pine, “Round c” in Figure 1.

Table 5. Collection of EWP (plywood, LVL, I-beam, glulam) strength distribution data together with lamellae tension and finger joint bending results. The type of distribution fitted to the lower tail data is given as well as the CO -parameter of the fitted distribution, the tail used for fitting as % of total sample and $f_{0.05}$ based on non-parametric distribution. Grade value is the expected 5th percentile strength according to the grade.

Product	Origin	Target $f_{0.05}$ [N/mm^2]	$f_{0.05}$ in test [N/mm^2]	Explanation of test	Sample size	Tail fitted [%]	Fitting distribution	COV [%]	Reference
I-beam	Norway	24	25.8	Standard bending test	294	10	Normal Log-normal	12 17	NTI
Finger joint	Norway	24	22.8	Edgewise bending	620	10	Normal Log-normal	20 33	NTI
Finger joint	Norway	30	24.9	Edgewise bending	220	10	Normal Log-normal	27 57	NTI
Glulam	Norway	30	33.5	Edgewise bending	126	10	Normal Log-normal	11 13	NTI
Glulam	Norway	37	39.9	Edgewise bending	109	10	Normal Log-normal	14 19	NTI
Glulam lamellae	Scandinavia	20	19.2	Tension	1098	30	Normal Log-normal 2-P Weibull	21 30 18	Dalsgaard Sorensen, Hoffmeyer Table 3.15, Cook Bolinder
Glulam lamellae	Scandinavia	20	19.4	Tension	1079	30	Normal Log-normal 2-P Weibull	21 30 18	Dalsgaard Sorensen, Hoffmeyer Table 3.16, Computermatic
Glulam lamellae	Scandinavia	16	17.0	Tension	549	30	Normal Log-normal 2-P Weibull	22 33 20	Dalsgaard Sorensen, Hoffmeyer Table 3.17, Dynadrade
LVL	Spruce, Kerto	50	51.3	Edgewise bending	1968	10	Normal Log-normal 2-P Weibull	8 9 5	Ranta-Maunus et al. Table 2.13, “LVL edge” in Figure 1.
LVL	Spruce, Kerto	50	50.3	Flatwise bending	1963	10	Normal Log-normal 2-P Weibull	10 12 6	Ranta-Maunus et al. Table 2.13, “LVL flat” in Figure 1.
Plywood	Spruce, 3 mm ply	30	33.6	Flatwise bending	281	10	Normal Log-normal 2-P Weibull	16 23 11	Ranta-Maunus et al. Table 2.17, “Ply S3.0” in Figure 1.