Statistical Analysis of Data for Timber Strengths

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Abstract

Statistical analyses are performed for material strength parameters from approximately 6700 specimens of structural timber. Non-parametric statistical analysis and fits to the following distribution types have been investigated: Normal, Lognormal, 2 parameter Weibull and 3-parameter Weibull. The statistical fits have generally been made using all data (100%) and the lower tail (30%) of the data. The Maximum Likelihood Method and the Least Square Technique have been used to estimate the statistical parameters in the selected distributions. 8 different databases are analyzed. The results show that the 2-parameter Weibull (and Normal) distributions give the best fits to the data available, especially if tail fits are used whereas the LogNormal distribution generally gives a poor fit and larger coefficients of variation, especially if tail fits are used.

Bending, tension and compression strengths approximately have a coefficient of variation, COV equal to 20 %, 25% and 15% if 2-parameter Weibull tail fits are used. If a LogNormal distribution is fitted then the COVs are approximately 25%, 30% and 15%. Therefore it seems reasonable to introduce different partial safety factors for bending, tension and compression strength. Characteristic values (5 % quantiles) varies significantly compared to 'target' values. Generally visual grading gives larger estimated values than target values. Cook-Bolinder and Computermatic machine gradings give lower estimated values than target values, whereas Dynagrade machine grading gives slightly larger estimated values than target values. It is noted that the standard machine settings are used.

Reliability investigations show that if the same reliability level is used as in the Danish structural codes from 1998, then partial safety factors g_R = 1.5, 1.6 and 1.7 are reasonable values for COV = 0.15, 0.20 and 0.25 when the strength is LogNormal distributed. If the strength is modeled by a 2-parameter Weibull distribution then the reliability level is significantly lower. Higher partial safety factors has to be used for COV's equal to 0.20 and 0.25 compared to those for LogNormal distributed strengths.

Acknowledgements

This report is prepared in connection with the research project 'Reliability of Timber Structures' supported by 'The National Forest and Nature Agency
made available by Carl-Johan Johansson and Charlotte Bengtsson of the Swedish National Testing and Research Institute (SP).

Contents

1 Introduction

This report describes statistical analyses performed for material strength parameters from specimens of structural timber. Non-parametric statistical analysis and fits to the following distribution types have been investigated:

- Normal
- Lognormal
- 2 parameter Weibull
- 3-parameter Weibull

The statistical fits have generally been made using all data (100%) and the lower tail (generally 30%) of the data with lowest strength. The Maximum Likelihood Method has been used to estimate the statistical parameters in the selected distributions. The theoretical background for estimating the statistical parameters is described in section 2. In section 3 to 10 the statistical results from analyzing 8 different databases are shown. Finally in section 10 reliability levels and partial safety factors are discussed on the basis of the results of the statistical analyses.

1.1 Data bases

The statistical analyses have been carried out for 8 different data bases including a total of approximately 6700 pieces of structural lumber. Most of the data are from timber of Nordic origin, but even Norway spruce from France and Germany and sitka spruce from Ireland have been included.

Visual grading is predominantly based on the Nordic T-rules as laid down in [1]. For database C, an earlier version of the T-rules was used. However, for the purpose of the present investigation, the differences between the two sets of rules are insignificant.

Machine grading has been analysed from the results of three machines, which are presently the most important machines for the Scandinavian market. Two of these, Computermatic and Cook-Bolinder, are based on an assessment of the static bending stiffness, while the third, Dynagrade, is based on an assessment of the dynamic modulus of elasticity by a non-destructive measurement of the axial eigenfrequency. For the purpose of the present investigation three standard machine grades are used: M18, M24 and M30. These grades correspond to the visual grades T1, T2 and T3. The official so-called indicating properties for these machine grades are shown in table 1.1.

	Indicating property		
	M18	M24	M30
Computermatic	5595	6950	8860
Cook-Bolinder	5595	6950	8860
Dynagrade	4430000	5840000	7000000

Table 1.1. Machine settings for machine grading.

It should be noted that the results of machine grading for the bending machines Cook-Bolinder and Computermatic are dependent on thickness of the board and grading speed (e.g.: [17])

The machine settings of Table 1.1 are officially used throughout the range 34-50 mm. As a result, too high values of the indicating property are produced for thin boards. The resultant yield will be too high, and consequently thin dimensions will show relatively too low characteristic strength values.

High grading speed typical of commercial production (of the order 90 m/min) introduces dynamic beam behavior, which will result in a lowering of characteristic values. For this reason, the grading speed typical of the present data banks is usually chosen to be quite low (of the order 40 m/min). As a result, commercial grading of the present data banks would have resulted in downgrading of a number of boards and consequently produced higher characteristic values for the remainder of the grade.

As a rule all data have been adjusted to meet the requirements of EN 384 [12] with respect to corrections for moisture contents different from the reference condition and sizes different from the reference size.

The target characteristic values for the various visual grades and machine grades are those of the strength classes (K-classes) as defined in the Danish Timber Code, DS 413 [13]. These values are given in table 1.2. For reasons of comparison the values of the C-classes of the corresponding European standard (EN 338 [14)]) are also given. There are no strength classes assigned to the LT-grades of glulam lamellas (database A), but rather to the glulam produced from these lamellas.

Strength Class, DS 413:1998	K14	K18	K24	K30
characteristic bending strength, f_{mk} (MPa)	14	18	24	30
characteristic compression strength, $f_{c,0,k}$ (MPa)	12	15	20	26
characteristic tensile strength, $f_{t,0,k}$ (MPa)	8	10	16	20
Strength Class, EN 338:1998	C14	C18	C24	C30
characteristic bending strength, f_{mk} (MPa)	14	18	24	30
characteristic compression strength, $f_{c,0,k}$ (MPa)	16	18	21	23
characteristic tensile strength, $f_{t,0,k}$ (MPa)	8	11	14	18
Visual grade, INSTA 142:1997	T0	T1	T2	T3
Earlier Nordic T-grades		T18	T24	T30
Machine grade		M18	M24	M30

Table 1.2. Target characteristic values.

The following eight databases have been investigated:

Database A
1600 specimens of Norway spruce glulam laminations (40 x 145 mm) subjected to tension or bending. Visual grading and machine grading. [6].

Database B
284 specimens (45 x 145 mm) of Norway spruce subjected to bending. Machine grading. [7].

Database C
500 specimens (two dimensions) of Norway spruce subjected to bending or tension. Visual grading and machine grading. [8].

Database F
1794 specimens (two dimensions) of Norway spruce and a small amount of Scots pine subjected to bending. Machine grading. [9].

Database H
500 specimens (two dimensions) of Irish grown sitka spruce subjected to bending. Visual grading. [10].

Database I
500 specimens (three dimensions) of French grown Norway spruce subjected to bending. Visual grading.

Database J
850 specimens (45 x 145 mm) of Swedish grown Norway spruce subjected to bending, compression or tension. Visual grading

Database K
700 specimens (45 x 145 mm) of Danish grown sitka spruce subjected to bending or tension. Visual grading. [11]

2 Theoretical background

This chapter describes the statistical distributions used in the statistical analyses, the parameter estimation by the Maximum Likelihood Method and the estimation of characteristic values using reliability techniques.

2.1 Distributions

The following four distribution types have been used:

Normal distribution

The distribution function is written:

$$F_X(x) = \Phi\left(\frac{x-m}{s}\right) = \int_{-\infty}^{x} \frac{1}{\sqrt{2ps}} \exp\left(-\left(\frac{x-m}{s}\right)^2\right) dx \qquad (1)$$

where m is the expected value and s is the standard deviation. $\Phi(.)$ is the distribution function for a standardized normal distributed stochastic variable.

Lognormal distribution

The distribution function is written:

$$F_X(x) = \Phi\left(\frac{\ln x - m_Y}{s_Y}\right) \quad , \quad x > 0 \qquad (2)$$

where m_Y and s_Y are parameters related to the expected value m and the standard deviation s of X by

$$s_Y = \sqrt{\ln\left(\left(\frac{s}{m}\right)^2 + 1\right)} \qquad (3)$$

$$m_Y = \ln m - \frac{1}{2} s_Y^2 \qquad (4)$$

2-parameter Weibull distribution

The distribution function is written

$$F_X(x) = 1 - \exp\left(-\left(\frac{x}{b}\right)^a\right) \quad , \quad x \geq 0 \qquad (5)$$

where a is the shape parameter and b is the scale parameter. These are related to the expected value m and the standard deviation s of X by

$$m = b\,\Gamma\left(1 + \frac{1}{a}\right) \qquad (6)$$

$$s = b\sqrt{\Gamma\left(1 + \frac{2}{a}\right) - \Gamma^2\left(1 + \frac{1}{a}\right)} \qquad (7)$$

3-parameter Weibull distribution

The distribution function is written

$$F_X(x) = 1 - \exp\left(-\left(\frac{x-g}{b-g}\right)^a\right) \quad , \quad x \geq g \tag{8}$$

where g is the threshold, a is the shape parameter and b is the scale parameter. These are related to the expected value m and the standard deviation s of X by

$$m = (b-g)\,\Gamma\left(1+\frac{1}{a}\right) + g \tag{9}$$

$$s = (b-g)\sqrt{\Gamma\left(1+\frac{2}{a}\right) - \Gamma^2\left(1+\frac{1}{a}\right)} \tag{10}$$

2.2 Parameter estimation

If all data are used then the parameter estimation is performed with the Maximum Likelihood Method, see section 2.2.1. If fits to the lower tail is made then the least square technique is used, see section 2.2.2. Generally the statistical analyses are only performed if the number of data is larger than 20. This means that if tail fits are made to the lowest 30% of the data then in total more than 67 data has to be available.

2.2.1 Maximum Likelihood Method (MLM)

The statistical parameters, for example a and b, are determined using the Maximum-Likelihood method. The Log-Likelihood function is written, e.g. for the truncated Weibull distribution:

$$\ln L(a,b) = \ln\left(\prod_{i=1}^{n} f_X(x_i)\right) = \sum_{i=1}^{n} \ln\left(\frac{a}{P_0}\left(\frac{x_i}{b}\right)^{a-1} \exp\left(-\left(\frac{x_i}{b}\right)^a\right)\right) \tag{11}$$

where $f_X(x)$ is the density function and x_i , $i = 1, n$ are the n data available. The optimization problem $\max_{a,b} \ \ln L(a,b)$ is solved using a standard nonlinear optimizer (in this report the NLPQL algorithm is used, see [2]).

Because the parameters a and b are determined using a limited number of data they are subject to statistical uncertainty. Since the parameters are estimated by the Maximum Likelihood technique they become asymptotically (number of data should be larger than 25-30) Normally distributed stochastic variables with expected values equal to the Maximum Likelihood estimators and covariance matrix equal to, see e.g. Lindley, [3]

$$C_{a,b} = [-H_{ab}]^{-1} = \begin{bmatrix} s_a^2 & r_{ab}\, s_a s_b \\ r_{ab}\, s_a s_b & s_b^2 \end{bmatrix} \tag{12}$$

where $H_{\alpha\beta}$ is the Hessian matrix with second order derivatives of the log-Likelihood function. σ_α and σ_β denote the standard deviations of α and β, respectively. $\rho_{\alpha\beta}$ is the correlation coefficient between α and β. The Hessian matrix is estimated by numerical differentiation.

2.2.2 Tail fit by the Least Square Technique (LST)

The unknown parameters in a given distribution function $F_X(x|\theta)$ for a stochastic variable X are denoted $\theta = (\theta_1, \theta_2, \ldots, \theta_m)$.

The observations / data $\hat{\mathbf{x}} = (\hat{x}_1, \hat{x}_2, \ldots, \hat{x}_n)$ are ranked such that $\hat{x}_1 \le \hat{x}_2 \le \ldots \le \hat{x}_n$. An empirical distribution function is then established, e.g. using the Weibull – plot formula:

$$\hat{F}_i = \frac{i}{n+1} \quad , x = \hat{x}_i \tag{13}$$

The statistical parameters are determined from the optimization problem

$$\min_{\theta} \sum_{i=1}^{N} \left(\hat{F}_i - F_X(x_i) \right)^2 \tag{14}$$

where $N = n$ if all data are used. If a fit to the lower tail is to be determined then $N = \kappa\, n$ where κ is the fraction of the data used. The solution of this optimization problem gives a central estimate of the statistical parameters $\theta = (\theta_1, \theta_2, \ldots, \theta_m)$.

2.3 Characteristic values

The characteristic value x_q corresponding to the $q \cdot 100$ % quantile of the stochastic variable X is defined by

$$F_X(x_q) = P(X \le x_q) = q \quad \rightarrow \quad x_q = F_X^{-1}(q) \tag{15}$$

If statistical uncertainty is taken into account the characteristic value is determined considering the limit state function:

$$g = X - x_q \tag{16}$$

The characteristic value x_q is defined by

$$q = P\left(X \le x_q\right) = P(g \le 0) = P(g(X, \alpha, \beta, h_q) \le 0) \tag{17}$$

It is seen that X becomes dependent on the three stochastic variables X, α and β. The transformation to standard Normal space (U_1, U_2, U_3) is established using a Rosenblatt transformation.

If for example X is Weibull distributed the transformation can be written:

$$U_1 = \frac{\boldsymbol{a} - m_a}{\boldsymbol{s}_a} \qquad \text{solved for } \boldsymbol{a} \tag{18}$$

$$\boldsymbol{r}_{ab} U_1 + \sqrt{1 - \boldsymbol{r}_{ab}^2}\, U_2 = \frac{\boldsymbol{b} - m_b}{\boldsymbol{s}_b} \qquad \text{solved for } \boldsymbol{b} \tag{19}$$

$$\Phi(U_3) = 1 - \exp\left(- \left(\frac{X - g}{\boldsymbol{b} - g} \right)^a \right) \qquad \text{solved for } X \tag{20}$$

The probability $P(g(X, \boldsymbol{a}, \boldsymbol{b}, x_q) \leq 0)$ can then be estimated by the First Order Reliability Method (FORM) (see [4] and [5]) and/or by Monte Carlo simulation where realizations of (U_1, U_2, U_3) are simulated and X is determined by the Rosenblatt transformation (18)-(20). x_q is determined iteratively from (17).

3 Database A

3.1 Contents of database

Species	Norway spruce
Number of specimens	1600
Dimensions	40 x 145 mm
Origin	The material was collected from eight mills in Scandinavia: Two in Finland, two in Norway and four in Sweden. From each sawmill 150 pieces were collected for tension tests. From each of four of the eight mills an additional 100 pieces were sampled for bending tests. These four mills were chosen to be one from Norway, one from Finland and two from Sweden.
Loading mode	Tension and bending
Quality	Normal quality for glulam laminations
Pre-grading	Visual pre-grading according to the LT-grades for glulam lamination took place at the sawmills. Half the material was selected as LT20; the other half was selected as LT 30
Visual grading	Visual grading at laboratories to classes: LT10, LT20, LT30 and LT40
Machine grading	Machine grading to classes: M18, M24 and M30 Grading machines included: Computermatic, Cook-Bolinder and Dynagrade
More information	[6]
Remarks	A limited number of specimens of dimensions other than 40 x 145 mm are available in the databank. However, these specimens are not included in the statistical analyses.

3.2 Bending strength

3.2.1 Visual graded data

Table 3.1 shows the basic statistical characteristics for the visual graded strength data.

	LT10	LT20	LT30	LT40
Number of data	21	194	109	74
Expected value	32.4	39.6	49.6	58.7
COV	0.19	0.26	0.24	0.22
Min. value	20.0	15.9	20.6	29.1
Max. value	42.5	65.3	76.0	85.9
$x_{0.05}$	20.2	21.6	29.8	36.7

Table 3.1 Statistical data (in MPa).

In the following tables and figures are shown the results obtained using the visual graded data when fits to the following four distributions are performed:

- Normal
- Lognormal
- 2 parameter Weibull
- 3-parameter Weibull with g chosen as 0.9 times the smallest strength value.

Tail fits are made using k =10%, 15%, …, 40% and 100% of the data. The Least Square Technique (LST) is used as well as the Maximum Likelihood Method (MLM) when 100% data is used. As results are shown the coefficient of variation, COV ($= s / m$) and the characteristic value, $x_{0.05}$ defined as the 5% quantile.

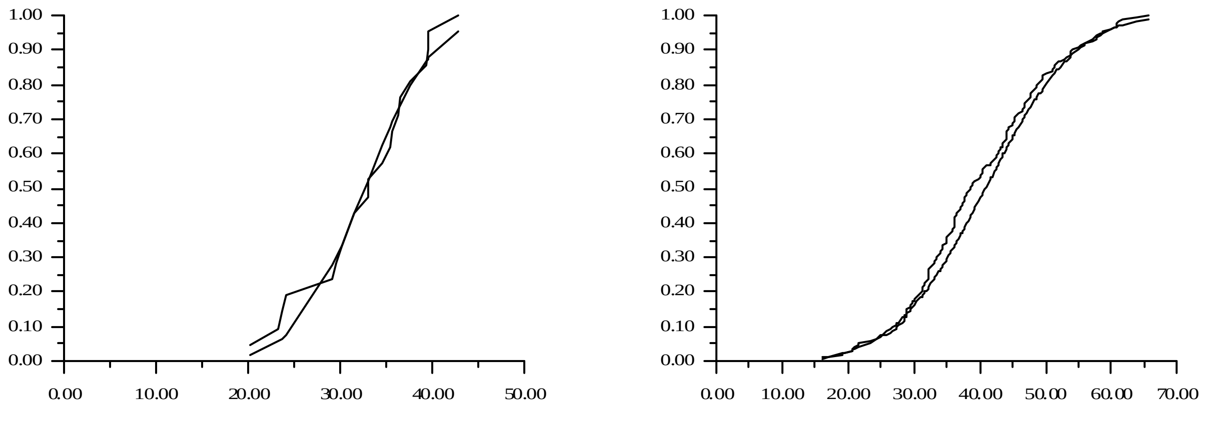
3.2.1.1 Normal distribution

Table 3.2 and figures 3.1 – 3.5 show the results if fits to the Normal distribution are made. It is seen that:

- generally the smallest COV is obtained if the distribution function is fitted to all data.
- only small deviations for the 5% quantiles are observed.
- the 5% quantile is higher than that corresponding to grading classes LT10 and LT20 and smaller than that corresponding to grading class LT40.
- the two estimation methods, LST and MLM give slightly different results for 100% data. Deviations up to 3% are observed for the characteristic value estimate.

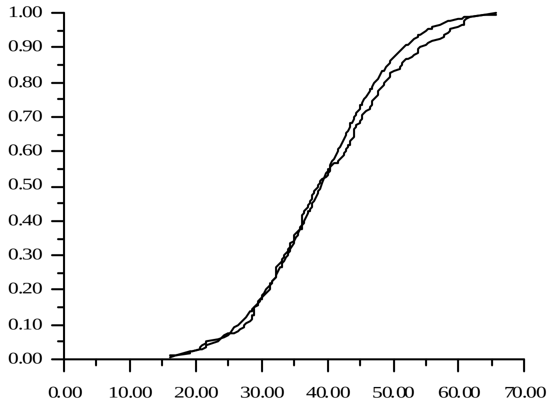
	LT10		LT20		LT30		LT40	
Number of data	21		194		109		74	
Truncation, k	COV	$x_{0.05}$	COV	$x_{0.05}$	COV	$x_{0.05}$	COV	$x_{0.05}$
10%			0.26	22.6	0.28	28.7	0.24	35.8
15%			0.27	22.7	0.27	28.5	0.24	35.6
20%	0.20	19.5	0.26	22.7	0.27	28.5	0.25	35.6
25%			0.26	22.7	0.27	28.5	0.25	35.7
30%			0.25	22.7	0.26	28.7	0.24	35.8
35%			0.25	22.8	0.26	28.7	0.24	35.8
40%			0.25	22.8	0.26	28.7	0.24	35.9
100% (LST)			0.27	22.0	0.24	29.7	0.22	37.1
100% (MLM)	0.18	22.6	0.26	22.4	0.23	30.6	0.21	38.2

Table 3.2 Statistical data (in MPa) for Normal fit.

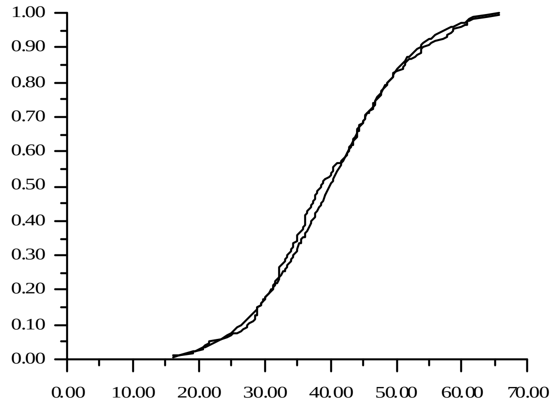


LT10: k =100% truncation LT20: k =15% truncation

Figure 3.1 Distribution fits (in MPa).

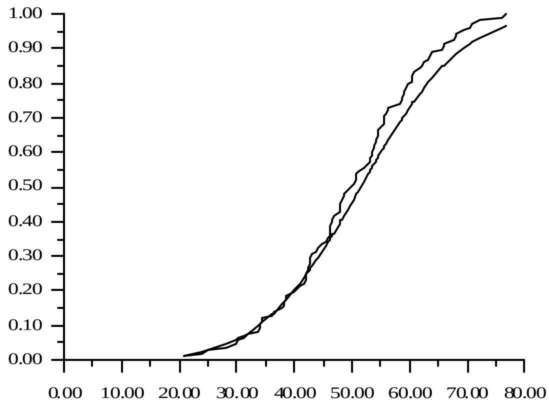


LT20: k =30% truncation

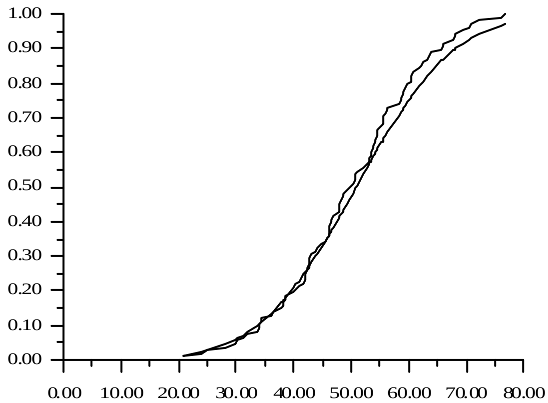


LT20: k =100% truncation

Figure 3.2 Distribution fits (in MPa).

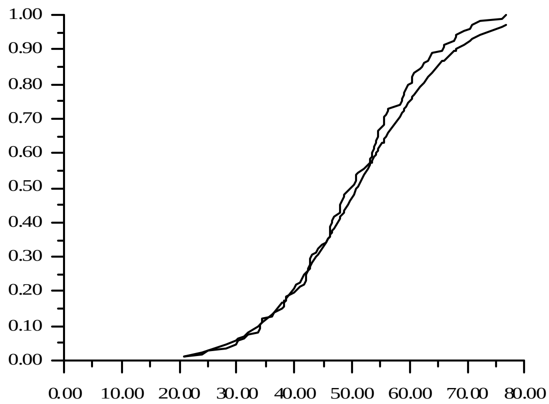


LT30: k =15% truncation

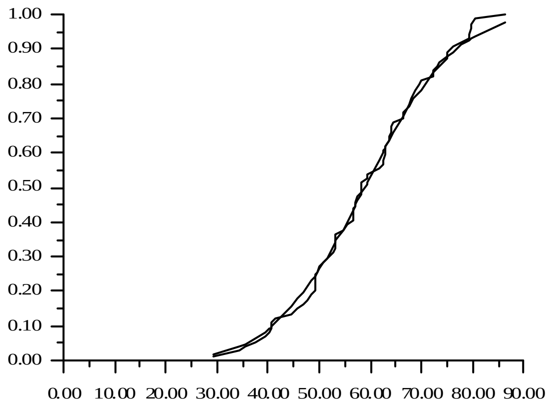


LT30: k =30% truncation

Figure 3.3 Distribution fits (in MPa).

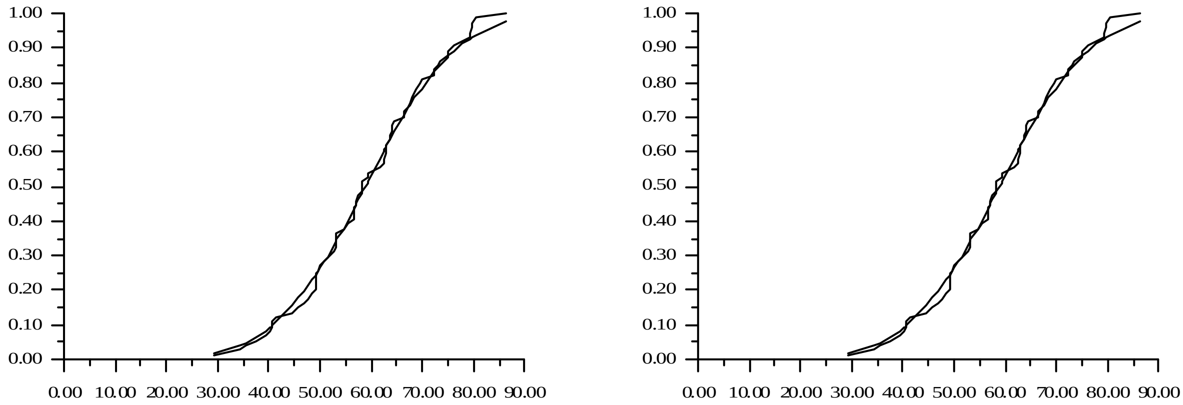


LT30: k =100% truncation



LT40: k =15% truncation

Figure 3.4 Distribution fits (in MPa).



LT40: k =30% truncation   LT40: k =100% truncation

Figure 3.5 Distribution fits (in MPa).

For the fits where all data are used it is possible to estimate the statistical uncertainty as described in section 2.2 and to estimate the 5% quantile with statistical uncertainty included as described in section 2.3. The results are shown in table 3.3. It is seen that

- the statistical uncertainties for the two parameters m and s are small and that only marginal differences for the 5% quantile are obtained if statistical uncertainty is included.

	m	s	$V[m]$	$V[s]$	$r[m,s]$	$x_{0.05}$ - stat	$x_{0.05}$ + stat
LT10	32.4	5.9	0.040	0.155	0.046	22.6	22.3
LT20	39.6	10.4	0.019	0.051	0.011	22.4	22.4
LT30	49.6	11.6	0.023	0.068	0.027	30.6	30.6
LT40	58.7	12.4	0.025	0.082	0.049	38.2	38.0

Table 3.3 Statistical uncertainty. $x_{0.05}$ - stat and $x_{0.05}$ + stat indicate the 5% quantile estimates without and with statistical uncertainty included (in MPa).

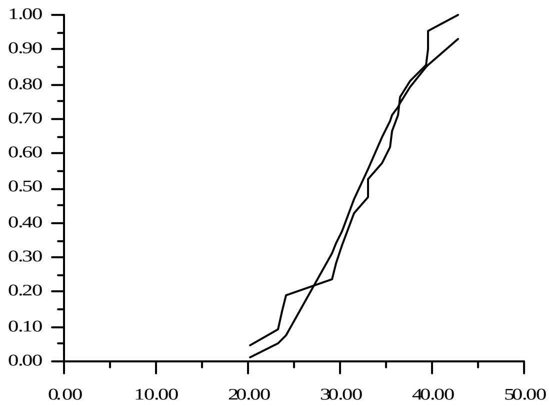
3.2.1.2 Logormal distribution

Table 3.4 and figures 3.6 – 3.10 show the results if fits to the Lognormal distribution are made. It is seen that:

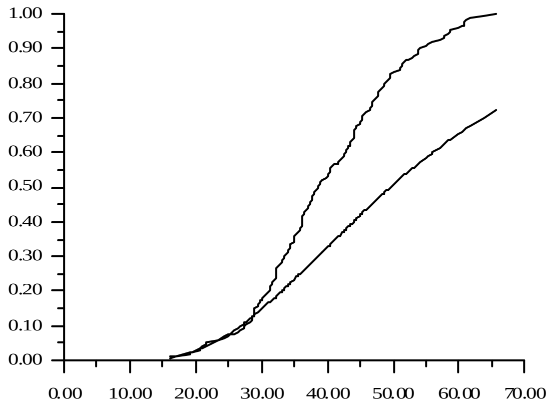
- generally the smallest COV is obtained if the distribution function is fitted to all data.
- large deviations between the data and the fitted distribution are observed if the fit is made with only 15% or 30% of the data.
- small deviations for the 5% quantiles are observed – but the 5% quantile (when all data are used) is in all cases larger than the one obtained if fits are made to the lower tail.
- the 5% quantile is higher than that corresponding to grading classes LT10 and LT20 and LT30 and smaller than that corresponding to grading class LT40.
- LST gives up to 4% larger estimates for the characteristic value than MLM, while the smaller COV estimates are obtained.

	LT10		LT20		LT30		LT40	
Number of data	21		194		109		74	
Truncation, k	COV	$x_{0.05}$	COV	$x_{0.05}$	COV	$x_{0.05}$	COV	$x_{0.05}$
10%			0.54	22.4	0.58	28.4	0.41	35.6
15%			0.51	22.3	0.48	28.2	0.38	35.5
20%	0.25	19.7	0.45	22.4	0.45	28.3	0.40	35.4
25%			0.41	22.5	0.43	28.4	0.37	35.6
30%			0.38	22.8	0.40	28.7	0.34	35.9
35%			0.36	22.8	0.38	28.9	0.33	36.1
40%			0.35	22.9	0.36	29.1	0.32	36.3
100% (LST)			0.26	25.1	0.23	33.1	0.20	40.7
100% (MLM)	0.20	23.0	0.28	24.1	0.26	31.8	0.23	39.5

Table 3.4 Statistical data (in MPa) for Lognormal fit.

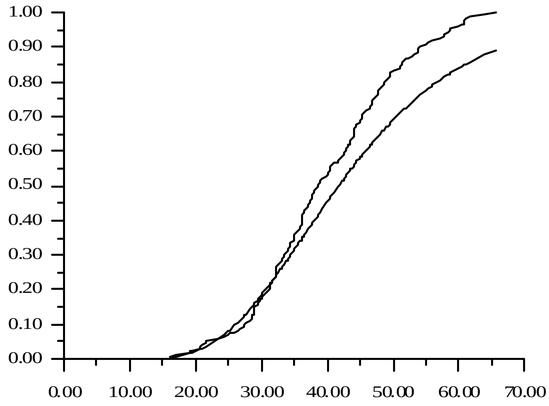


LT10: k =100% truncation

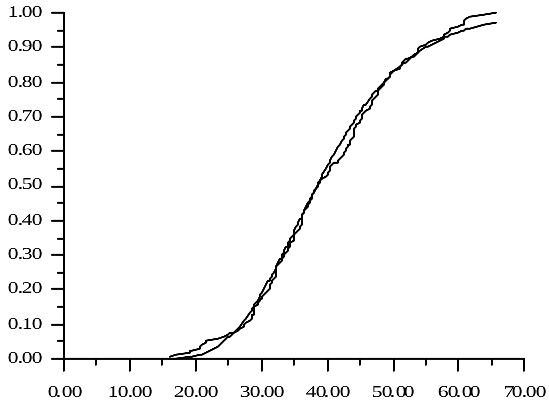


LT20: k =15% truncation

Figure 3.6 Distribution fits (in MPa).

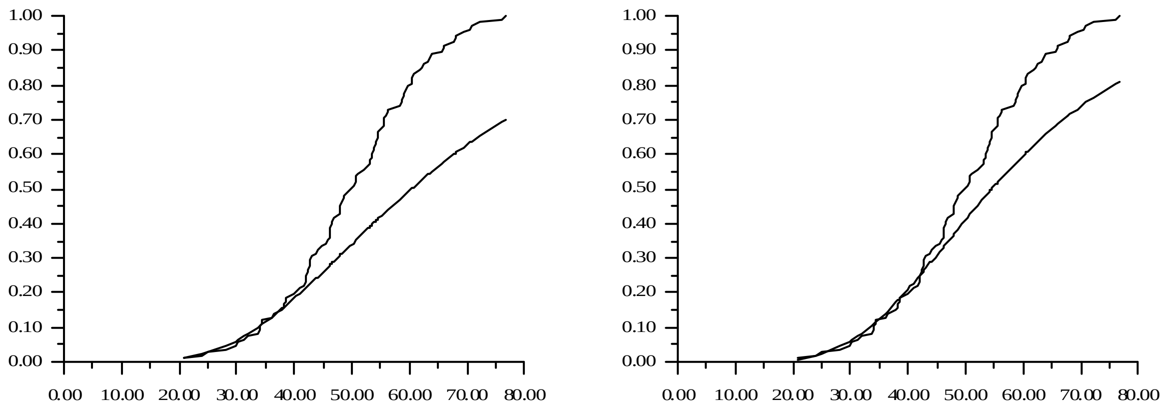


LT20: k =30% truncation



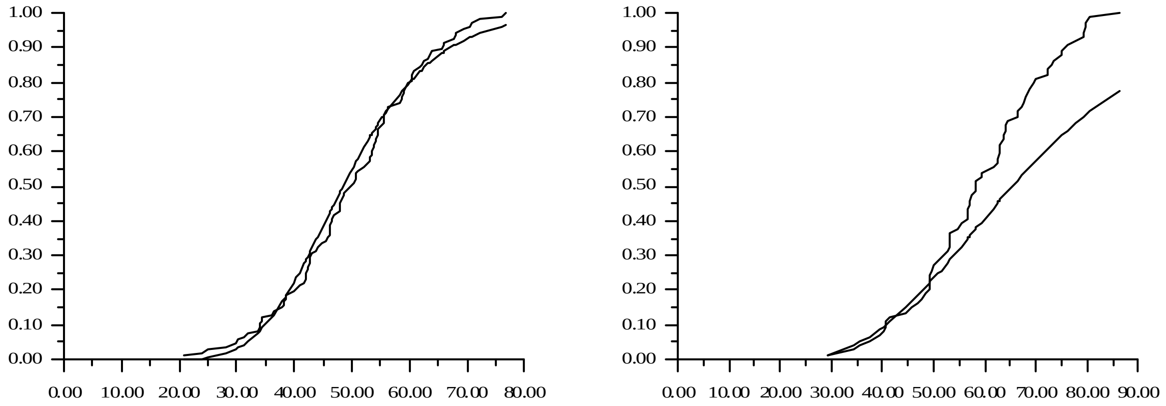
LT20: k =100% truncation

Figure 3.7 Distribution fits (in MPa).



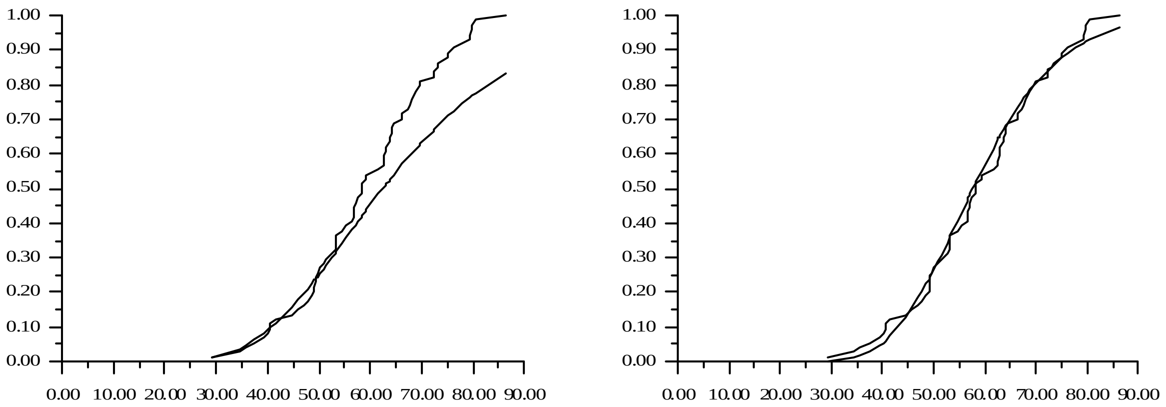
LT30: κ =15% truncation LT30: κ =30% truncation

Figure 3.8 Distribution fits (in MPa).



LT30: κ =100% truncation LT40: κ =15% truncation

Figure 3.9 Distribution fits (in MPa).



LT40: κ =30% truncation LT40: κ =100% truncation

Figure 3.10 Distribution fits (in MPa).

For the fits where all data are used it is possible to estimate the statistical uncertainty as described in section 2.2 and to estimate the 5% quantile with statistical uncertainty included as described in section 2.3. The results are shown in table 3.5. It is seen that

- the statistical uncertainties for the two parameters μ_Y and σ_Y are small and that only marginal differences for the 5% quantile are obtained if statistical uncertainty is included.

	m_Y	s_Y	$V[m_Y]$	$V[s_Y]$	$r[m_Y, s_Y]$	$x_{0.05}$ - stat	$x_{0.05}$ + stat
LT10	31.8	0.198	0.043	0.157	0.001	23.0	22.7
LT20	38.3	0.279	0.020	0.050	0.000	24.1	24.1
LT30	48.3	0.254	0.024	0.067	0.001	31.8	31.7
LT40	57.4	0.226	0.026	0.084	0.001	39.5	39.4

Table 3.5 Statistical uncertainty. $x_{0.05}$ - stat and $x_{0.05}$ + stat indicate the 5% quantile estimates without and with statistical uncertainty included (in MPa).

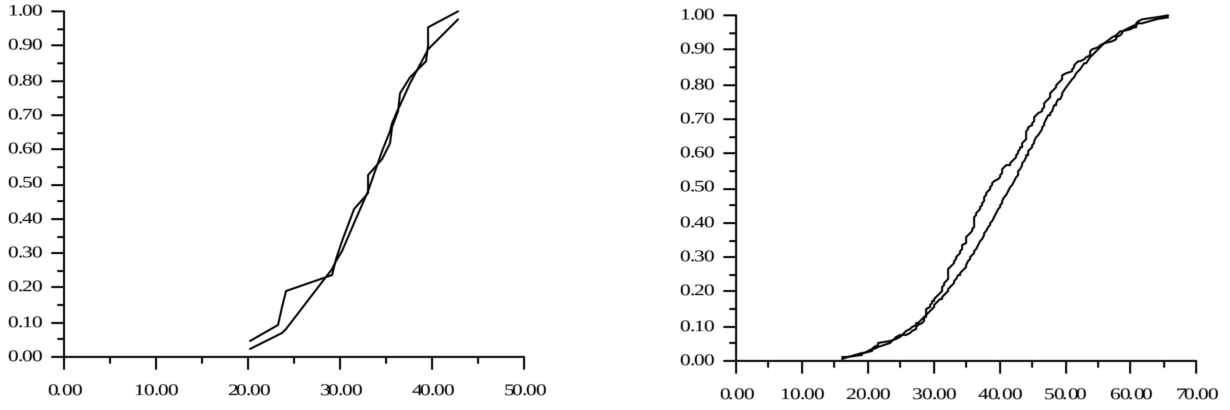
3.2.1.3 2 parameter Weibull distribution

Table 3.6 and figures 3.11 – 3.15 show the results if fits to the 2 parameter Weibull distribution are made. It is seen that:

- generally the smallest COV is obtained if the distribution function is fitted to the lower tail (30-40% of the data).
- small deviations for the 5% quantiles are observed – in most cases the 5% quantile is larger than the one obtained if fits are made to the lower tail.
- the 5% quantile is higher than that corresponding to grading classes LT10 and LT20 and smaller than that corresponding to grading classes LT30 and LT40.
- LST gives up to 2% smaller estimates for the characteristic value than MLM, while the COV estimates are identical.

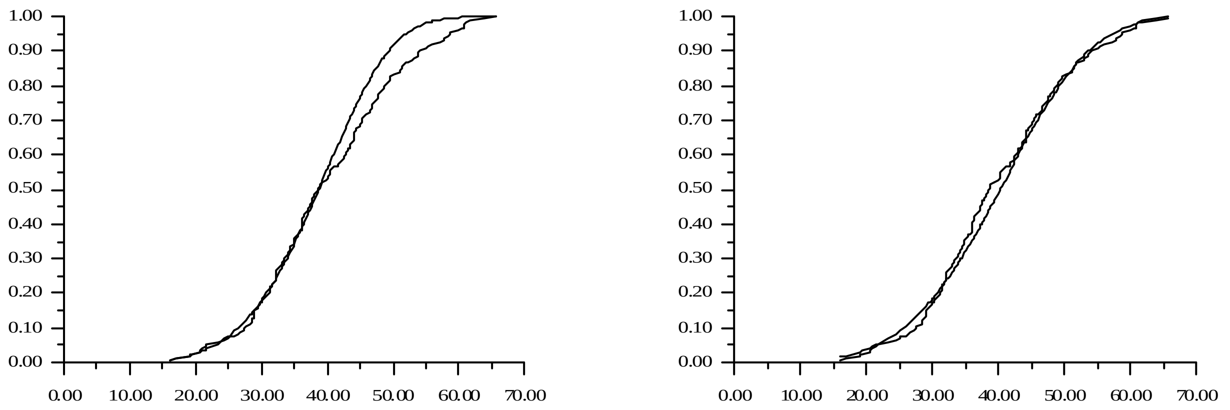
	LT10		LT20		LT30		LT40	
Number of data	21		194		109		74	
Truncation, k	COV	$x_{0.05}$	COV	$x_{0.05}$	COV	$x_{0.05}$	COV	$x_{0.05}$
10%			0.26	22.5	0.28	28.6	0.22	35.8
15%			0.26	22.6	0.26	28.5	0.21	35.6
20%	0.17	19.4	0.25	22.6	0.25	28.5	0.23	35.6
25%			0.24	22.6	0.25	28.5	0.23	35.6
30%			0.23	22.8	0.25	28.7	0.22	35.8
35%			0.23	22.8	0.24	28.8	0.22	35.8
40%			0.23	22.8	0.24	28.8	0.21	35.9
100% (LST)			0.27	21.1	0.24	28.6	0.22	35.8
100% (MLM)	0.18	22.2	0.27	21.3	0.24	29.2	0.22	36.5

Table 3.6 Statistical data (in MPa) for 2 parameter Weibull fit.



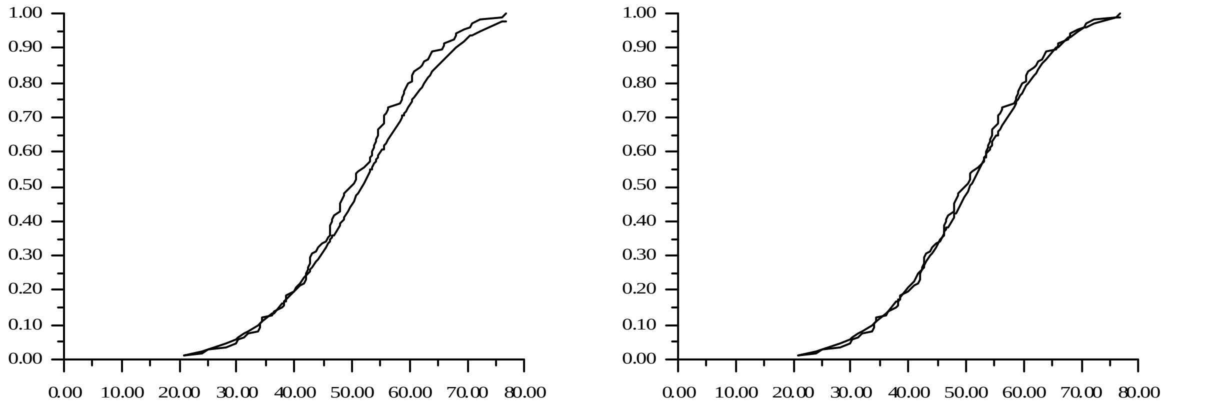
LT10: k =100% truncation LT20: k =15% truncation

Figure 3.11 Distribution fits (in MPa).



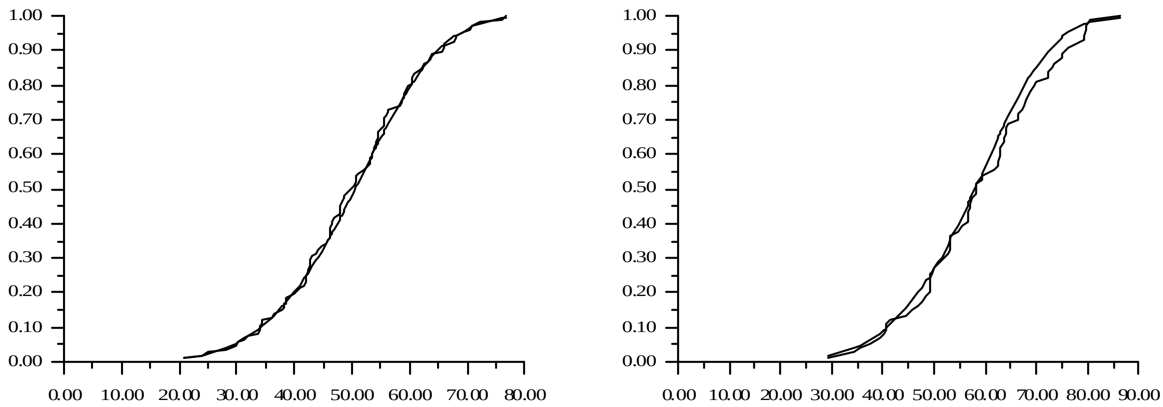
LT20: k =30% truncation LT20: k =100% truncation

Figure 3.12 Distribution fits (in MPa).



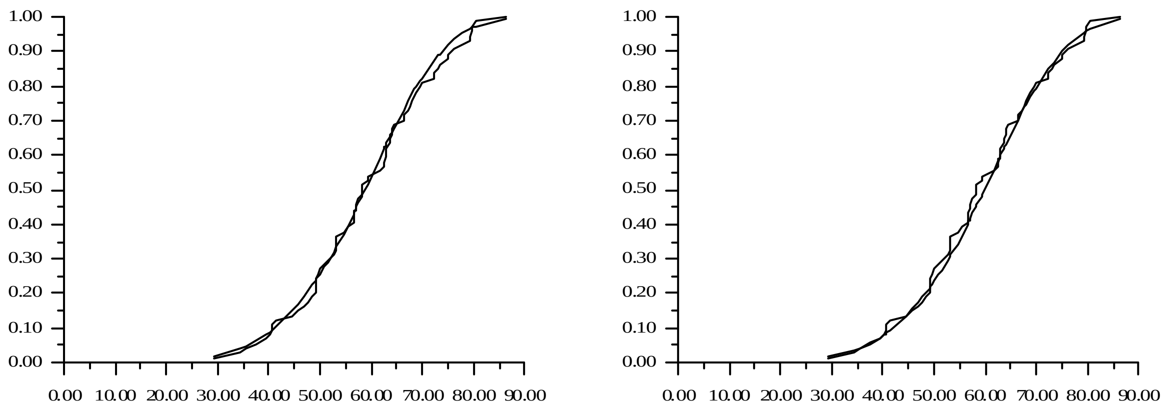
LT30: k =15% truncation LT30: k =30% truncation

Figure 3.13 Distribution fits (in MPa).



LT30: k =100% truncation   LT40: k =15% truncation

Figure 3.14 Distribution fits (in MPa).



LT40: k =30% truncation   LT40: k =100% truncation

Figure 3.15 Distribution fits (in MPa).

For the fits where all data are used it is possible to estimate the statistical uncertainty as described in section 2.2 and to estimate the 5% quantile with statistical uncertainty included as described in section 2.3. The results are shown in table 3.7. It is seen that

- generally the statistical uncertainties for the two parameters b and a are small and that only marginal differences for the 5% quantile are obtained if statistical uncertainty is included. However, for LT10 where the number of data is small, the statistical uncertainty has some influence.

	b	a	$V[b]$	$V[a]$	$r[b,a]$	$x_{0.05}$ - stat	$x_{0.05}$ + stat
LT10	6.58	34.8	0.173	0.034	0.35	22.2	21.5
LT20	4.17	43.7	0.051	0.018	0.053	21.3	21.3
LT30	4.79	54.3	0.073	0.021	0.011	29.2	29.1
LT40	5.33	63.9	0.089	0.023	0.19	36.5	36.4

Table 3.7 Statistical uncertainty. $x_{0.05}$ - stat and $x_{0.05}$ + stat indicate the 5% quantile estimates without and with statistical uncertainty included (in MPa).

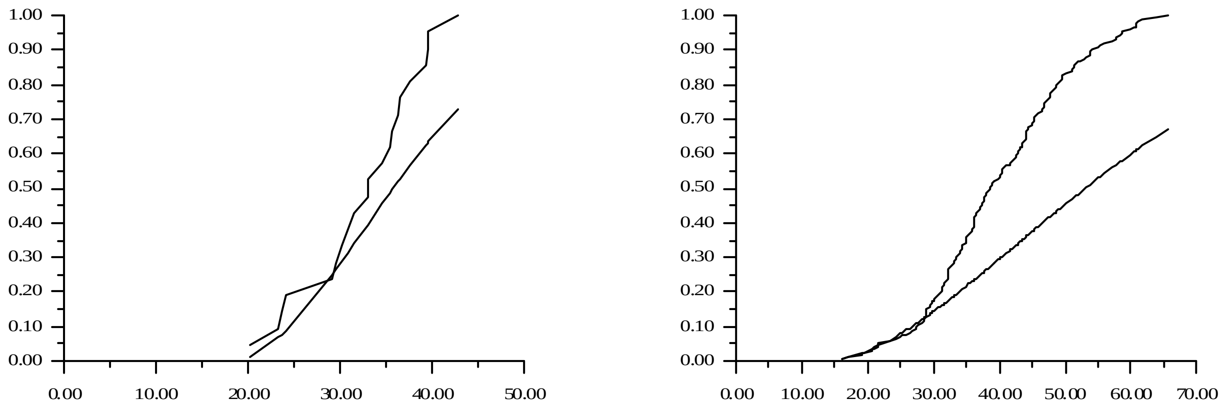
3.2.1.4 3 parameter Weibull distribution

Table 3.8 and figures 3.16 – 3.20 show the results if fits to the 3 parameter Weibull distribution are made. It is seen that:

- generally the smallest COV is obtained if the distribution function is fitted to all data.
- large deviations between the data and the fitted distribution are observed if the fit is made with only 15% or 30% of the data.
- small deviations for the 5% quantiles are observed – but the 5% quantile is in all cases larger than the one obtained if fits are made to the lower tail.
- the 5% quantile is higher than that corresponding to grading classes LT10 and LT20 and smaller than that corresponding to grading class LT40.
- almost identical estimates for characteristic values and COV are obtained using LST and MLM.

	LT10		LT20		LT30		LT40	
Number of data	21		194		109		74	
Truncation, k	COV	$x_{0.05}$	COV	$x_{0.05}$	COV	$x_{0.05}$	COV	$x_{0.05}$
10%			0.58	22.0	0.57	28.2	0.47	35.4
15%			0.46	22.1	0.42	28.2	0.39	35.4
20%	0.30	20.1	0.37	22.3	0.38	28.3	0.41	35.3
25%			0.33	22.5	0.36	28.5	0.35	35.7
30%			0.30	22.8	0.32	28.9	0.30	36.2
35%			0.28	22.9	0.30	29.0	0.29	36.3
40%			0.28	23.0	0.29	29.2	0.27	36.6
100% (LST)			0.26	23.3	0.23	30.8	0.21	39.0
100% (MLM)	0.18	23.2	0.26	23.3	0.23	31.1	0.21	39.0

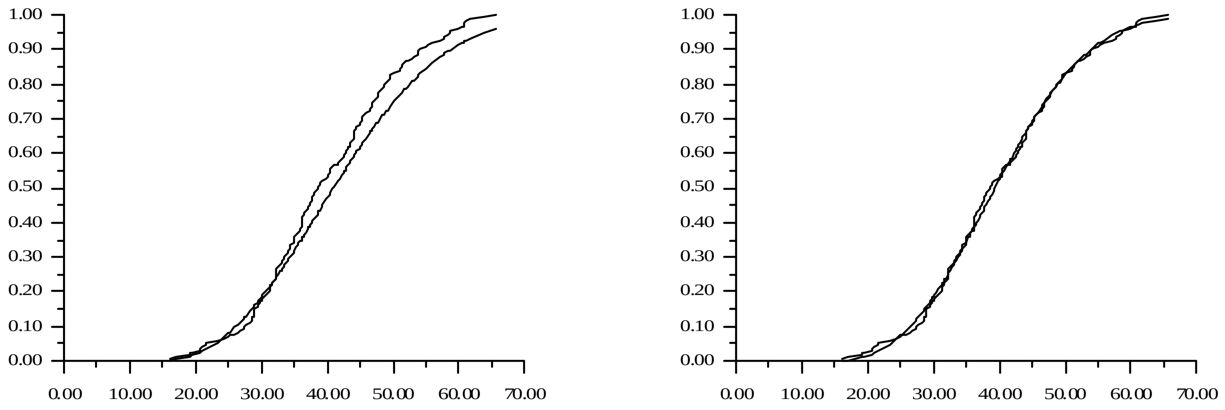
Table 3.8 Statistical data (in MPa) for 3 parameter Weibull fit.



LT10: k =100% truncation

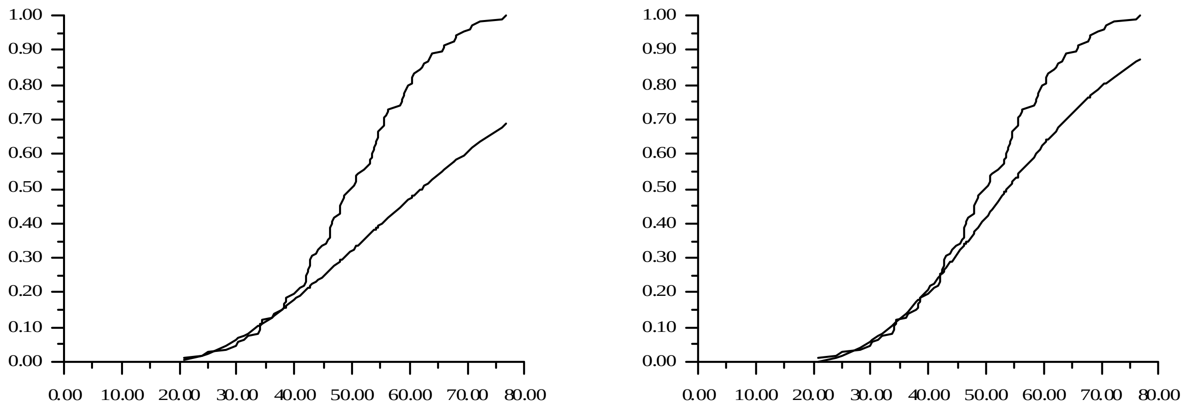
LT20: k =15% truncation

Figure 3.16 Distribution fits (in MPa).



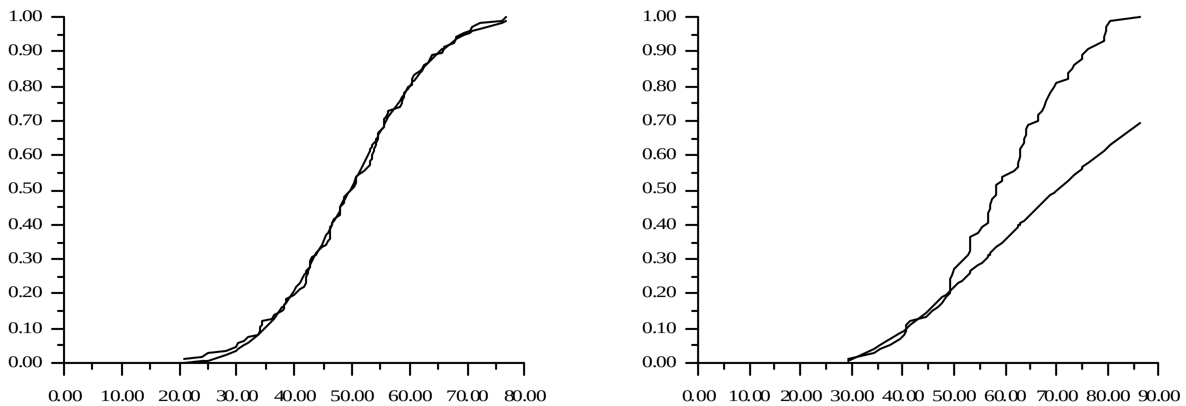
LT20: k =30% truncation LT20: k =100% truncation

Figure 3.17 Distribution fits (in MPa).



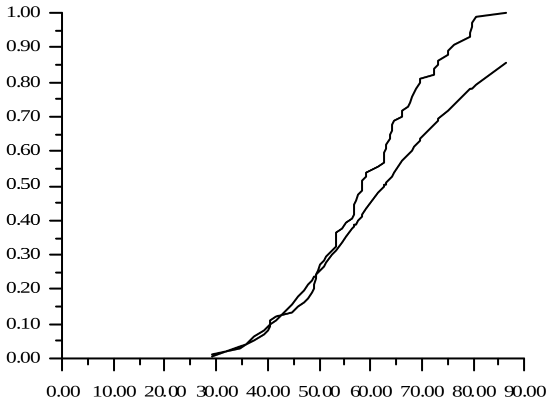
LT30: k =15% truncation LT30: k =30% truncation

Figure 3.18 Distribution fits (in MPa).

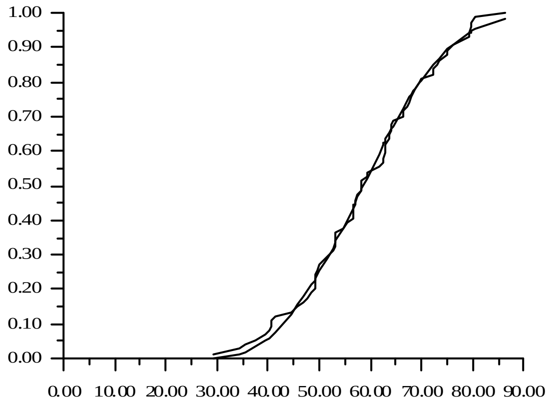


LT30: k =100% truncation LT40: k =15% truncation

Figure 3.19 Distribution fits (in MPa).



LT40: k =30% truncation



LT40: k =100% truncation

Figure 3.20 Distribution fits (in MPa).

For the fits where all data are used it is possible to estimate the statistical uncertainty as described in section 2.2 and to estimate the 5% quantile with statistical uncertainty included as described in section 2.3. The results are shown in table 3.9. It is seen that

- generally the statistical uncertainties for the two parameters b and a are small and that only marginal differences for the 5% quantile are obtained if statistical uncertainty is included.

	b	a	g	$V[b]$	$V[a]$	$r[b,a]$	$x_{0.05}$ - stat	$x_{0.05}$ + stat
LT10	1.88	21.3	18.0	-	-	-	23.2	-
LT20	2.65	28.9	14.0	0.057	0.028	0.036	23.3	23.3
LT30	2.98	35.5	18.0	0.077	0.034	0.076	31.1	30.9
LT40	2.88	36.8	26.0	0.093	0.042	0.12	39.0	38.9

Table 3.9 Statistical uncertainty. $x_{0.05}$ - stat and $x_{0.05}$ + stat indicate the 5% quantile estimates without and with statistical uncertainty included (in MPa).

3.2.1.5 Summary

Table 3.10 summarizes the above results. The results for tail fits correspond to using 30% of the data. It is seen that

- the 2 parameter Weibull distribution gives the smallest COV (=0.18 – 0.25).
- the LogNormal distribution gives rather large COV’s
- the characteristic values for the two commonly used grades LT20 and LT30 are of the same order as those defined for strength classes K24 and K30.

	LT10		LT20		LT30		LT40	
Number of data	21		194		109		74	
	COV	$x_{0.05}$	COV	$x_{0.05}$	COV	$x_{0.05}$	COV	$x_{0.05}$
Non-parametric	0.19	20.2	0.26	21.6	0.24	29.8	0.22	36.7
Normal Normal - tail	0.18	22.6	0.26 0.25	22.4 22.7	0.23 0.26	30.6 28.7	0.21 0.24	38.2 35.8
LogNormal LogNormal - tail	0.20	23.0	0.28 0.38	24.1 22.8	0.26 0.40	31.8 28.7	0.23 0.34	39.5 35.9
Weibull-2p Weibull-2p - tail	0.18	22.2	0.27 0.23	21.3 22.8	0.24 0.25	29.2 28.7	0.22 0.22	36.5 35.8
Weibull-3p Weibull-3p - tail	0.18	23.2	0.26	23.3	0.23	31.1	0.21	39.0
Target $x_{0.05}$	not defined							

Table 3.10. Statistical data (in MPa).

3.2.2 Machine graded data

3.2.2.1 Cook-Bolinder

Table 3.11 summarizes the results for machine graded data by the Cook-Bolinder machine. The results for tail fits correspond to using 30% of the data. It is seen that

- the 2 parameter Weibull distribution gives the smallest COV (=0.21 – 0.32).
- the LogNormal distribution gives rather large COV's
- the characteristic values are generally much smaller than the target characteristic values.

	M18		M24		M30	
Number of data	1		22		386	
	COV	$x_{0.05}$	COV	$x_{0.05}$	COV	$x_{0.05}$
Non-parametric			0.33	16.0	0.29	27.1
Normal Normal – tail			0.32	14.9	0.29 0.23	24.2 26.3
LogNormal LogNormal - tail			0.32	17.7	0.31 0.34	27.0 26.1
Weibull-2p Weibull-2p - tail			0.34	13.9	0.30 0.21	23.1 26.2
Weibull-3p Weibull-3p - tail			0.32	17.6	0.29 0.28	26.1 26.1
Target $x_{0.05}$		18		24		30

Table 3.11. Statistical data (in MPa).

3.2.2.2 Computermatic

	M18		M24		M30	
Number of data	4		33		371	
	COV	$x_{0.05}$	COV	$x_{0.05}$	COV	$x_{0.05}$
Non-parametric			0.29	16.5	0.29	27.2
Normal Normal - tail			0.29	17.7	0.29 0.23	24.5 26.5
LogNormal LogNormal - tail			0.31	19.3	0.30 0.33	27.3 26.3
Weibull-2p Weibull-2p - tail			0.29	17.0	0.30 0.20	23.4 26.4
Weibull-3p Weibull-3p - tail			0.29	19.2	0.29 0.28	26.4 26.3
Target $x_{0.05}$		18		24		30

Table 3.12 Statistical data (in MPa).

Table 3.12 summarizes the results for machine graded data by the Computermatic machine. The results for tail fits correspond to using 30% of the data. It is seen that

- the 2 parameter Weibull distribution gives the smallest COV (=0.20 – 0.29).
- the LogNormal distribution gives rather large COV's
- the characteristic values are generally much smaller than the target characteristic values.

3.2.2.3 Dynagrade

	M18		M24		M30	
Number of data	41		176		156	
	COV	$x_{0.05}$	COV	$x_{0.05}$	COV	$x_{0.05}$
Non-parametric	0.34	18.8	0.25	24.9	0.25	31.1
Normal Normal - tail	0.33 0.28	14.8 16.7	0.25 0.24	24.1 24.5	0.25 0.23	31.1 30.9
LogNormal LogNormal - tail	0.32 0.43	18.7 16.8	0.27 0.35	25.8 24.4	0.27 0.35	33.1 30.7
Weibull-2p Weibull-2p - tail	0.36 0.27	13.7 16.6	0.26 0.21	22.6 24.5	0.26 0.21	29.7 30.8
Weibull-3p Weibull-3p - tail	0.33 0.48	18.1 17.1	0.25 0.28	24.8 24.5	0.33 0.25	32.6 30.5
Target $x_{0.05}$		18		24		30

Table 3.13. Statistical data (in MPa).

Table 3.13 summarizes the results for machine graded data by the Dynagrade machine. The results for tail fits correspond to using 30% of the data. It is seen that

- the 2 parameter Weibull distribution gives the smallest COV (=0.21 – 0.27).
- the LogNormal distribution gives rather large COV's
- the characteristic values are generally close to the target characteristic values.

3.3 Tensile strength – full database

3.3.1 Visual graded data

Table 3.14 summarizes the results for visual graded data. The results for tail fits correspond to using 30% of the data. It is seen that

- the 2 parameter Weibull distribution gives the smallest COV (=0.20 – 0.29).
- the LogNormal distribution gives rather large COV's
- the characteristic values are generally much larger than the target characteristic values.

	LT10		LT20		LT30		LT40	
Number of data	70		503		288		122	
	COV	$x_{0.05}$	COV	$x_{0.05}$	COV	$x_{0.05}$	COV	$x_{0.05}$
Non-parametric	0.30	13.5	0.31	16.9	0.27	22.0	0.30	22.5
Normal	0.30	12.3	0.31	14.0	0.27	19.9	0.30	21.3
Normal - tail	0.29	12.1	0.23	16.5	0.24	20.8	0.25	22.9
LogNormal	0.32	13.8	0.31	16.5	0.29	21.7	0.31	24.3
LogNormal - tail	0.48	12.2	0.33	16.4	0.36	20.7	0.37	22.9
Weibull-2p	0.31	11.7	0.33	13.0	0.28	18.7	0.31	19.9
Weibull-2p - tail	0.29	12.1	0.20	16.5	0.22	20.8	0.23	22.9
Weibull-3p	0.30	13.2	0.31	14.9	0.27	20.6	0.30	23.4
Weibull-3p - tail	0.40	12.3	0.24	16.4	0.28	20.7	0.33	23.0
Target $x_{0.05}$				16		20		

Table 3.14. Statistical data (in MPa).

3.3.2 Machine graded data

3.3.2.1 Cook-Bolinder

Table 3.15 summarizes the results for machine graded data by the Cook-Bolinder machine. The results for tail fits correspond to using 30% of the data. It is seen that

- the 2 parameter Weibull distribution gives the smallest COV (=0.18 – 0.22).
- the LogNormal distribution gives rather large COV's
- the characteristic values are generally smaller than the target characteristic values, especially for the M24 grading.

	M18		M24		M30	
Number of data	3		94		1098	
	COV	$x_{0.05}$	COV	$x_{0.05}$	COV	$x_{0.05}$
Non-parametric			0.31	11.6	0.32	19.2
Normal Normal - tail			0.31 0.24	10.1 11.5	0.32 0.21	15.9 19.2
LogNormal LogNormal - tail			0.29 0.36	12.2 11.5	0.32 0.30	18.9 19.0
Weibull-2p Weibull-2p - tail			0.35 0.22	8.7 11.5	0.33 0.18	15.0 19.2
Weibull-3p Weibull-3p - tail			0.31 0.32	11.3 11.5	0.32 0.23	17.4 19.0
Target $x_{0.05}$		10		16		20

Table 3.15. Statistical data (in MPa).

3.3.2.2 Computermatic

Table 3.16 summarizes the results for machine graded data by the Computermatic machine. The results for tail fits correspond to using 30% of the data. It is seen that

- the 2 parameter Weibull distribution gives the smallest COV (=0.18 – 0.23).
- the LogNormal distribution gives rather large COV's
- the characteristic values are generally much smaller than the target characteristic values, especially for the M24 grading.

	M18		M24		M30	
Number of data	7		109		1079	
	COV	$x_{0.05}$	COV	$x_{0.05}$	COV	$x_{0.05}$
Non-parametric			0.26	12.9	0.31	19.4
Normal Normal - tail			0.25 0.25	12.3 12.5	0.31 0.21	16.1 19.4
LogNormal LogNormal - tail			0.26 0.37	13.4 12.5	0.32 0.30	19.1 19.2
Weibull-2p Weibull-2p - tail			0.28 0.23	11.1 12.5	0.33 0.18	15.1 19.3
Weibull-3p Weibull-3p - tail			0.26 0.31	12.6 12.5	0.31 0.22	17.5 19.2
Target $x_{0.05}$		10		16		20

Table 3.16. Statistical data (in MPa).

3.3.2.3 Dynagrade

Table 3.17 summarizes the results for machine graded data by the Dynagrade machine. The results for tail fits correspond to using 30% of the data. It is seen that

- the 2 parameter Weibull distribution gives the smallest COV (=0.18 – 0.27).
- the LogNormal distribution gives rather large COV's
- the characteristic values are generally close to the target characteristic values.

	M18		M24		M30	
Number of data	120		549		485	
	COV	$x_{0.05}$	COV	$x_{0.05}$	COV	$x_{0.05}$
Non-parametric	0.26	12.5	0.27	17.0	0.26	24.5
Normal	0.25	12.6	0.27	15.5	0.26	22.8
Normal – tail	0.28	12.1	0.22	16.8	0.20	24.7
LogNormal	0.27	13.4	0.27	17.2	0.26	25.1
LogNormal - tail	0.45	12.0	0.33	16.7	0.29	24.5
Weibull-2p	0.27	11.7	0.29	14.1	0.28	20.8
Weibull-2p - tail	0.27	12.0	0.20	16.8	0.18	24.7
Weibull-3p	0.26	12.9	0.27	15.7	0.26	23.7
Weibull-3p - tail	0.39	12.0	0.24	16.7	0.24	24.4
Target $x_{0.05}$		10		16		20

Table 3.17. Statistical data (in MPa).

3.4 Tensile strength – reduced database - 4 selected sawmills (Sawmills identical to those selected for bending tests)

3.4.1 Visual graded data

	LT10		LT20		LT30		LT40	
Number of data	44		238		134		67	
	COV	$x_{0.05}$	COV	$x_{0.05}$	COV	$x_{0.05}$	COV	$x_{0.05}$
Non-parametric	0.30	11.0	0.33	17.2	0.27	22.2	0.28	23.9
Normal	0.29	12.3	0.33	13.2	0.26	21.1	0.28	22.9
Normal - tail			0.23	16.1	0.24	21.5	0.24	23.9
LogNormal	0.32	13.4	0.33	16.0	0.28	22.8	0.28	25.6
LogNormal - tail			0.33	16.0	0.36	21.5	0.34	24.0
Weibull-2p	0.30	11.7	0.34	12.6	0.27	19.9	0.30	21.1
Weibull-2p - tail			0.20	16.1	0.22	21.5	0.21	23.9
Weibull-3p	0.29	13.0	0.33	14.5	0.26	21.6	0.28	24.9
Weibull-3p - tail			0.24	16.1	0.27	21.5	0.31	24.3
Target $x_{0.05}$				10		16		

Table 3.18. Statistical data (in MPa).

Table 3.18 summarizes the results for visual graded data. The results for tail fits correspond to using 30% of the data. It is seen that

- the 2 parameter Weibull distribution gives the smallest COV (=0.20 – 0.22).
- the LogNormal distribution gives rather large COV's
- the characteristic values are generally much larger than the target characteristic values.

3.4.2 Machine graded data

3.4.2.1 Cook-Bolinder

Table 3.19 summarizes the results for machine graded data by the Cook-Bolinder machine. The results for tail fits correspond to using 30% of the data. It is seen that

- the 2 parameter Weibull distribution gives the smallest COV (=0.19).
- the LogNormal distribution gives rather large COV's
- the characteristic values are generally smaller than the target characteristic values, especially for the M24 grading.

	M18		M24		M30	
Number of data	2		40		564	
	COV	$x_{0.05}$	COV	$x_{0.05}$	COV	$x_{0.05}$
Non-parametric			0.29	10.5	0.32	18.9
Normal Normal – tail			0.28	10.4	0.32 0.22	15.8 19.0
LogNormal LogNormal - tail			0.31	11.3	0.33 0.32	18.9 18.7
Weibull-2p Weibull-2p - tail			0.28	10.0	0.34 0.19	15.1 18.9
Weibull-3p Weibull-3p - tail					0.32 0.24	17.5 18.7
Target $x_{0.05}$		10		16		20

Table 3.19. Statistical data (in MPa).

3.4.2.2 Computermatic

Table 3.20 summarizes the results for machine graded data by the Computermatic machine. The results for tail fits correspond to using 30% of the data. It is seen that

- the 2 parameter Weibull distribution gives the smallest COV (=0.20).
- the LogNormal distribution gives rather large COV's
- the characteristic values are generally much smaller than the target characteristic values, especially for the M24 grading.

	M18		M24		M30	
Number of data	4		55		547	
	COV	$x_{0.05}$	COV	$x_{0.05}$	COV	$x_{0.05}$
Non-parametric			0.28	11.0	0.32	19.0
Normal Normal – tail			0.28	11.9	0.32 0.23	16.0 18.8
LogNormal LogNormal - tail			0.29	13.2	0.33 0.34	18.9 18.6
Weibull-2p Weibull-2p - tail			0.44	8.4	0.33 0.20	15.3 18.8
Weibull-3p Weibull-3p - tail			0.28	12.6	0.32 0.26	17.5 18.6
Target $x_{0.05}$		10		16		20

Table 3.20. Statistical data (in MPa).

3.4.2.3 Dynagrade

Table 3.21 summarizes the results for machine graded data by the Dynagrade machine. The results for tail fits correspond to using 30% of the data. It is seen that

- the 2 parameter Weibull distribution gives the smallest COV (=0.18 – 0.27).
- the LogNormal distribution gives rather large COV's
- the characteristic values are generally close to or larger than the target characteristic values.

	M18		M24		M30	
Number of data	50		251		283	
	COV	$x_{0.05}$	COV	$x_{0.05}$	COV	$x_{0.05}$
Non-parametric	0.27	10.2	0.27	16.9	0.25	24.5
Normal Normal - tail	0.26	11.7	0.27 0.22	15.1 16.3	0.25 0.21	23.3 24.9
LogNormal LogNormal - tail	0.29	12.4	0.28 0.32	16.8 16.2	0.26 0.29	25.5 24.7
Weibull-2p Weibull-2p - tail	0.27	11.2	0.29 0.20	13.9 16.3	0.27 0.18	21.4 24.9
Weibull-3p Weibull-3p - tail			0.39 0.24	14.7 16.3	0.25 0.26	24.6 24.6
Target $x_{0.05}$		10		16		20

Table 3.21. Statistical data (in MPa).

3.4.3 Ratio of tensile strength to bending strength

The ratios of characteristic tensile strength to characteristic bending strength as they may be derived from DS 413 varies from 0.57 for low quality lumber (K14) to 0.67 for high quality lumber (K30).

The European standard for strength classes, EN338, establishes characteristic tensile strength values from characteristic bending strength values by using the ratio 0.60 for all strength classes.

Based on results from sections 3.2 and 3.4 ratios of characteristic tensile strength to characteristic bending strength may be assessed for some of the strength classes. Such ratios are presented in Table 3.22. The ratios are based on tail fits and are valid for both the 2 parameter Weibull distribution and the Normal distribution. The experimental values suggest that the Danish ratios and particularly the European ratio are too small.

Visual grading	LT20	LT30	LT40
INSTA 142	0.71	0.75	0.67
Machine grading		M24	M30
Cook-Bolinder			0.72
Computermatic			0.71
Dynagrade		0.67	0.81

Table 3.22. Ratios of characteristic tensile strength to characteristic bending strength. The ratios are based on tail fits and are valid for both 2 parameter Weibull and Normal distributions.

3.5 Summary for database A

The statistical results for the data show generally that

- the smallest COVs are obtained using the 2 parameter Weibull distribution fitted to 30% of the data.
- the fits to a Lognormal distribution results in rather large COVs and large deviations from observations at the upper part.
- the largest 5% quantile is obtained with fits to 30% of the data.
- for bending strength the COV is approximately 0.18 – 0.25 (tail fit to 2 parameter Weibull distribution)
- for tensile strength the COV is approximately 0.18 – 0.25 (tail fit to 2 parameter Weibull distribution)
- no significant difference in COV's is observed for visual and machine graded data
- the characteristic values (5% quantiles) are close to the target values for visual grading and machine grading by the Dynagrade machine and much smaller than the target values for the Cook-Bolinder and Computermatic machines.

4 Database B

4.1 Contents of database

Species	Norway spruce
Number of specimens	284
Dimensions	45 x 145 mm
Origin	The material was collected from seven mills in Sweden. About 40 pieces were collected from each mill.
Loading mode	Bending
Quality	Normal run-of-mill quality
Pre-grading	None
Visual grading	Visual grading at laboratories to classes: None
Machine grading	Machine grading to classes: M18, M24 and M30 Grading machines included: Cook-Bolinder
More information	[7]

4.2 Bending strength

4.2.1 Machine graded data

4.2.1.1 Cook-Bolinder

	M18		M24		M30	
Number of data	7		46		228	
	COV	$x_{0.05}$	COV	$x_{0.05}$	COV	$x_{0.05}$
Non-parametric			0.33	16.0	0.29	27.1
Normal Normal - tail			0.32 0.33	14.9 13.7	0.29 0.23	24.2 26.3
LogNormal LogNormal - tail			0.32 0.52	17.7 14.3	0.31 0.34	27.0 26.1
Weibull-2p Weibull-2p - tail			0.34 0.32	13.9 13.8	0.30 0.21	23.1 26.2
Weibull-3p Weibull-3p - tail			0.32 0.68	17.6 15.6	0.29 0.28	26.1 26.1
Target $x_{0.05}$		18		24		30

Table 4.1. Statistical data (in MPa).

Table 4.1 summarizes the results for machine graded data by the Cook-Bolinder machine. The results for tail fits correspond to using 30% of the data. It is seen that

- the 2 parameter Weibull distribution gives the smallest COV (=0.21 – 0.32).
- the LogNormal distribution gives rather large COV's
- the characteristic values are generally smaller than the target characteristic values, especially for the M24 grading.

5 Database C

5.1 Contents of database

Species	Norway spruce
Number of specimens	Approximately 500
Dimensions	34 x 145 mm and 58 x 120 mm
Origin	The material was collected from two mills in Sweden and one mill in Germany
Loading mode	Tension and bending
Quality	Normal run-of-mill quality
Pre-grading	Swedish timber: No pre-grading. German timber: Pre-grading to an equal number of the three German strength grades S7, S10 and S13
Visual grading	Visual grading at laboratories to Nordic T-rules [1]
Machine grading	Machine grading to classes: M18, M24 and M30 Grading machines included: Computermatic and Cook-Bolinder
More information	[8]
Remarks	

5.2 Bending strength

5.2.1 Visual grading

	K12		T18		T24		T30	
Number of data	8		80		106		44	
	COV	$x_{0.05}$	COV	$x_{0.05}$	COV	$x_{0.05}$	COV	$x_{0.05}$
Non-parametric			0.20	27.0	0.23	28.7	0.20	36.6
Normal			0.20	25.8	0.22	28.1	0.19	36.2
Normal - tail			0.19	26.4	0.19	28.2	0.18	36.3
LogNormal			0.20	27.5	0.24	29.6	0.19	38.1
LogNormal - tail			0.25	26.4	0.26	28.0	0.22	36.4
Weibull-2p			0.24	22.7	0.23	27.1	0.21	32.8
Weibull-2p - tail			0.16	26.4	0.16	28.1	0.15	36.2
Weibull-3p			0.20	26.7	0.22	29.6	0.19	37.8
Weibull-3p - tail			0.25	26.4	0.27	27.9	0.24	36.8
Target $x_{0.05}$		12		18		24		30

Table 5.1. Statistical data (in MPa).

Table 5.1 summarizes the results for visual graded data. The results for tail fits correspond to using 30% of the data. It is seen that

- the 2 parameter Weibull distribution gives the smallest COV (=0.15 – 0.16).
- the LogNormal distribution gives rather large COV’s
- the characteristic values are generally much larger than the target characteristic values (more than 20%).

5.2.2 Machine grading

5.2.2.1 Cook-Bolinder

Table 5.2 summarizes the results for machine graded data by the Cook-Bolinder machine. The results for tail fits correspond to using 30% of the data. It is seen that

- the COV is in the range =0.15 – 0.22.
- the characteristic values are smaller than the target characteristic values for the M24 grading and close to the target values for the M30 grading.

	M18		M24		M30	
Number of data	1		29		209	
	COV	$x_{0.05}$	COV	$x_{0.05}$	COV	$x_{0.05}$
Non-parametric			0.17	18.6	0.22	30.1
Normal Normal - tail			0.16	22.7	0.22	29.2
LogNormal LogNormal - tail			0.18	22.7	0.22	31.2
Weibull-2p Weibull-2p - tail			0.15	22.2	0.24	26.7
Weibull-3p Weibull-3p - tail			0.58	17.2	0.22	30.7
Target $x_{0.05}$		18		24		30

Table 5.2. Statistical data (in MPa).

5.2.2.2 Computermatic

	M18		M24		M30	
Number of data						
	COV	$x_{0.05}$	COV	$x_{0.05}$	COV	$x_{0.05}$
Non-parametric	0.21	18.1	0.18	27.8	0.19	35.0
Normal Normal - tail	 0.20	 21.3	0.18 0.20	27.0 26.5	0.19 0.20	34.9 34.2
LogNormal LogNormal - tail	 0.21	 22.2	0.19 0.27	27.8 26.5	0.20 0.26	36.1 34.2
Weibull-2p Weibull-2p - tail	 0.22	 19.6	0.20 0.17	24.9 26.5	0.21 0.17	32.1 34.2
Weibull-3p Weibull-3p - tail	 0.21	 21.9	0.19 0.21	26.5 26.6	0.19 0.24	35.2 34.2
Target $x_{0.05}$		18		24		30

Table 5.3. Statistical data (in MPa).

Table 5.3 summarizes the results for machine graded data by the Computermatic machine. The results for tail fits correspond to using 30% of the data. It is seen that

- the 2 parameter Weibull distribution gives the smallest COV (=0.17 – 0.22).
- the LogNormal distribution gives rather large COV's
- the characteristic values are generally larger than the target characteristic values, especially for the M24 and M30 gradings.

5.3 Analysis of modulus of elasticity, strength and density – correlation

In this section results are shown for the correlation between the following material parameters:

- Strength s
- Modulus of elasticity E
- Density $\boldsymbol{r}_S$

5.3.1 No grading

	Strength s	Modulus of Elasticity E	Density $\boldsymbol{r}_S$
Number of data	239		
Expected value	43.8	13 000	406
COV	0.25	0.19	0.09
$\boldsymbol{r}[s, E]$	0.84		
$\boldsymbol{r}[s, \boldsymbol{r}_S]$	0.39		
$\boldsymbol{r}[E, \boldsymbol{r}_S]$	0.51		

Table 5.4 Statistical data (in MPa).

5.3.2 Visual grading – T18

	Strength s	Modulus of Elasticity E	Density $\boldsymbol{r}_S$
Number of data	80		
Expected value	38.7	11 970	405
COV	0.20	0.17	0.09
$\boldsymbol{r}[s, E]$	0.77		
$\boldsymbol{r}[s, \boldsymbol{r}_S]$	0.52		
$\boldsymbol{r}[E, \boldsymbol{r}_S]$	0.62		

Table 5.5 Statistical data (in MPa).

5.3.3 Visual grading – T24

	Strength s	Modulus of Elasticity E	Density $\boldsymbol{r}_S$
Number of data	106		
Expected value	44.8	13 280	404
COV	0.23	0.18	0.08
$\boldsymbol{r}[s, E]$	0.85		
$\boldsymbol{r}[s, \boldsymbol{r}_S]$	0.49		
$\boldsymbol{r}[E, \boldsymbol{r}_S]$	0.64		

Table 5.6 Statistical data (in MPa).

5.3.4 Visual grading – T30

	Strength s	Modulus of Elasticity E	Density r_S
Number of data	44		
Expected value	52.9	14 800	415
COV	0.20	0.15	0.08
$r[s, E]$	0.69		
$r[s, r_S]$	0.46		
$r[E, r_S]$	0.64		

Table 5.7 Statistical data (in MPa).

5.3.5 Machine grading – Cook-Bolinder M30

	Strength s	Modulus of Elasticity E	Density r_S
Number of data	209		
Expected value	45.7	13 480	410
COV	0.22	0.16	0.08
$r[s, E]$	0.80		
$r[s, r_S]$	0.39		
$r[E, r_S]$	0.56		

Table 5.8 Statistical data (in MPa).

5.3.6 Machine grading – Computermatic M24

	Strength s	Modulus of Elasticity E	Density r_S
Number of data	103		
Expected value	38.5	11 720	394
COV	0.18	0.13	0.08
$r[s, E]$	0.73		
$r[s, r_S]$	0.19		
$r[E, r_S]$	0.44		

Table 5.9 Statistical data (in MPa).

5.3.7 Machine grading – Computermatic M30

	Strength s	Modulus of Elasticity E	Density r_S
Number of data	116		
Expected value	50.6	14 700	420
COV	0.19	0.14	0.07
$r[s, E]$	0.71		
$r[s, r_S]$	0.36		
$r[E, r_S]$	0.53		

Table 5.10 Statistical data (in MPa).

There are some variation in the correlation coefficients but generally the data indicates that

- The correlation coefficient between Strength s and Modulus of elasticity E is 0.8
- The correlation coefficient between Strength s and Density $\boldsymbol{r}_S$ is 0.4
- The correlation coefficient between Modulus of elasticity E and Density $\boldsymbol{r}_S$ is 0.6

5.4 Tensile strength

5.4.1 Visual grading

Table 5.11 summarizes the results for visual graded data. The results for tail fits correspond to using 30% of the data. It is seen that

- the 2 parameter Weibull distribution gives the smallest COV (=0.22 – 0.37).
- the LogNormal distribution gives rather large COV's
- the characteristic values are generally much larger than the target characteristic values.

	K12		T18		T24		T30	
Number of data	56		108		42		11	
	COV	$x_{0.05}$	COV	$x_{0.05}$	COV	$x_{0.05}$	COV	$x_{0.05}$
Non-parametric	0.37	10.3	0.38	13.8	0.32	19.2	0.23	18.9
Normal Normal – tail	0.36	9.2	0.37 0.29	11.1 13.7	0.31	19.2	0.21	30.9
LogNormal LogNormal - tail	0.40	11.2	0.43 0.46	13.8 13.8	0.35	21.1	0.21	32.9
Weibull-2p Weibull-2p - tail	0.37	9.2	0.39 0.28	10.9 13.7	0.30	19.3	0.22	28.5
Weibull-3p Weibull-3p - tail	0.51	10.7	0.38 0.33	13.0 13.9	0.31	20.9	0.27	34.5
Target $x_{0.05}$		8		10		16		20

Table 5.11. Statistical data (in MPa).

5.4.2 Machine grading

5.4.2.1 Cook-Bolinder

Table 5.12 summarizes the results for machine graded data by the Cook-Bolinder machine. The results for tail fits correspond to using 30% of the data. It is seen that

- the 2 parameter Weibull distribution gives the smallest COV (=0.24 – 0.36).
- the LogNormal distribution gives rather large COV's
- the characteristic values are generally much smaller than the target characteristic values.

	M18		M24		M30	
Number of data	0		14		203	
	COV	$x_{0.05}$	COV	$x_{0.05}$	COV	$x_{0.05}$
Non-parametric			0.40	4.1	0.39	15.6
Normal Normal – tail			0.37	6.3	0.39 0.26	11.2 15.0
LogNormal LogNormal - tail			0.42	7.6	0.40 0.40	15.2 15.0
Weibull-2p Weibull-2p - tail			0.36	6.6	0.40 0.24	11.7 15.0
Weibull-3p Weibull-3p - tail			0.38	7.5	0.39 0.29	13.7 15.0
Target $x_{0.05}$		10		16		20

Table 5.12. Statistical data (in MPa).

5.4.2.2 Computermatic

	M18		M24		M30	
Number of data	6		58		152	
	COV	$x_{0.05}$	COV	$x_{0.05}$	COV	$x_{0.05}$
Non-parametric			0.25	11.2	0.33	19.1
Normal Normal - tail			0.25	11.8	0.33 0.23	16.2 19.5
LogNormal LogNormal - tail			0.27	12.3	0.32 0.34	19.7 19.3
Weibull-2p Weibull-2p - tail			0.25	11.2	0.34 0.21	15.4 19.4
Weibull-3p Weibull-3p - tail			0.25	12.0	0.32 0.36	19.4 19.2
Target $x_{0.05}$		10		16		20

Table 5.13. Statistical data (in MPa).

Table 5.13 summarizes the results for machine graded data by the Computermatic machine. The results for tail fits correspond to using 30% of the data. It is seen that

- the 2 parameter Weibull distribution gives the smallest COV (=0.21 – 0.25).
- the LogNormal distribution gives rather large COV’s
- the characteristic values are generally smaller than the target characteristic values, especially for the M24 grading.

6 Database F

6.1 Contents of database

Species	Norway spruce and Scots pine (small amount)
Number of specimens	1794
Dimensions	Ten samples of 8 different dimensions ranging from 34 x 70 mm to 70 x 220 mm
Origin	The material was collected from three mills in Sweden and one mill in Finland
Loading mode	Bending
Quality	Normal run-of-mill quality
Pre-grading	None
Visual grading	None
Machine grading	Machine grading to classes: M18, M24 and M30 Grading machines included: Dynagrade
More information	[9]
Remarks	Remarks: The statistical analyses are carried out for each sample separately and for the total sample with size-corrected strength values.

6.2 Bending strength

6.2.1 Machine grading

The data are divided in 10 parts, A – J. Tables 6.1 – 6.11 summarizes the results for the 10 parts and for all data in the different parts analyzed together. It is seen that

- the 2 parameter Weibull distribution gives a COV approximately equal to 0.20.
- the LogNormal distribution gives large COV's
- the characteristic values are generally close to or slightly larger than the target characteristic values.

6.2.1.1 Part A – Dynagrade

	M18		M24		M30	
Number of data	17		85		50	
	COV	$x_{0.05}$	COV	$x_{0.05}$	COV	$x_{0.05}$
Non-parametric			0.25	25.9	0.21	31.8
Normal Normal - tail			0.24 0.25	25.3 24.5	0.20	35.3
LogNormal LogNormal - tail			0.27 0.35	26.6 24.8	0.23	35.9
Weibull-2p Weibull-2p - tail			0.25 0.22	24.1 24.6	0.20	34.6
Weibull-3p Weibull-3p - tail			0.24 0.26	25.7 24.9	0.20	36.2
Target $x_{0.05}$		18		24		30

Table 6.1. Statistical data (in MPa).

6.2.1.2 Part B – Dynagrade

	M18		M24		M30	
Number of data	25		109		65	
	COV	$x_{0.05}$	COV	$x_{0.05}$	COV	$x_{0.05}$
Non-parametric	0.20	18.0	0.28	22.2	0.26	31.4
Normal Normal - tail	0.19	19.1	0.27 0.24	19.9 20.9	0.25 0.21	30.5 31.2
LogNormal LogNormal - tail	0.25	21.3	0.28 0.34	22.1 20.8	0.26 0.30	33.2 31.1
Weibull-2p Weibull-2p - tail	0.20	18.2	0.29 0.21	18.3 20.9	0.27 0.19	28.6 31.1
Weibull-3p Weibull-3p - tail	0.19	19.7	0.28 0.26	20.7 20.8	0.25 0.34	33.1 31.2
Target $x_{0.05}$		18		24		30

Table 6.2. Statistical data (in MPa).

6.2.1.3 Part C – Dynagrade

	M18		M24		M30	
Number of data	47		114		31	
	COV	$x_{0.05}$	COV	$x_{0.05}$	COV	$x_{0.05}$
Non-parametric	0.31	18.0	0.28	31.3	0.25	31.9
Normal Normal - tail	0.30	17.6	0.28 0.23	28.1 29.8	0.24	39.4
LogNormal LogNormal - tail	0.33	19.8	0.29 0.32	31.3 29.8	0.28	40.8
Weibull-2p Weibull-2p - tail	0.31	17.2	0.29 0.20	26.3 29.8	0.24	38.3
Weibull-3p Weibull-3p - tail	0.31	19.2	0.28 0.29	30.4 29.7	0.25	40.2
Target $x_{0.05}$		18		24		30

Table 6.3. Statistical data (in MPa).

6.2.1.4 Part D – Dynagrade

	M18		M24		M30	
Number of data	12		74		82	
	COV	$x_{0.05}$	COV	$x_{0.05}$	COV	$x_{0.05}$
Non-parametric			0.23	28.4	0.23	29.8
Normal Normal - tail			0.22 0.28	24.9 23.4	0.23 0.26	32.1 29.2
LogNormal LogNormal - tail			0.31 0.40	23.1 24.1	0.25 0.40	33.1 29.3
Weibull-2p Weibull-2p - tail			0.24 0.26	22.6 23.8	0.22 0.25	31.3 29.2
Weibull-3p Weibull-3p - tail			0.25 0.26	22.6 23.9	0.23 0.38	33.1 29.6
Target $x_{0.05}$		18		24		30

Table 6.4. Statistical data (in MPa).

6.2.1.5 Part E – Dynagrade

	M18		M24		M30	
Number of data	11		67		99	
	COV	$x_{0.05}$	COV	$x_{0.05}$	COV	$x_{0.05}$
Non-parametric			0.29	21.2	0.22	32.8
Normal Normal - tail			0.29 0.26	20.8 20.6	0.22 0.21	33.6 33.2
LogNormal LogNormal - tail			0.31 0.38	22.8 20.7	0.23 0.29	35.1 33.3
Weibull-2p Weibull-2p - tail			0.29 0.24	20.3 20.6	0.23 0.18	31.6 33.2
Weibull-3p Weibull-3p - tail			0.29 0.34	22.5 20.9	0.22 0.24	34.3 33.5
Target $x_{0.05}$		18		24		30

Table 6.5. Statistical data (in MPa).

6.2.1.6 Part F – Dynagrade

	M18		M24		M30	
Number of data	2		59		90	
	COV	$x_{0.05}$	COV	$x_{0.05}$	COV	$x_{0.05}$
Non-parametric			0.19	25.3	0.22	31.5
Normal Normal - tail			0.19 0.20	25.9 24.8	0.22 0.23	32.2 31.7
LogNormal LogNormal - tail			0.19 0.26	26.7 24.9	0.23 0.32	33.8 31.8
Weibull-2p Weibull-2p - tail			0.20 0.17	24.3 24.8	0.23 0.21	30.0 31.7
Weibull-3p Weibull-3p - tail			0.19 0.22	26.1 25.1	0.22 0.28	33.0 32.1
Target $x_{0.05}$		18		24		30

Table 6.6. Statistical data (in MPa).

6.2.1.7 Part G – Dynagrade

	M18		M24		M30	
Number of data	18		79		59	
	COV	$x_{0.05}$	COV	$x_{0.05}$	COV	$x_{0.05}$
Non-parametric	0.21	20.5	0.26	25.5	0.19	37.3
Normal Normal - tail	0.20	22.1	0.26 0.29	24.3 23.2	0.19 0.18	36.9 36.5
LogNormal LogNormal - tail	0.20	23.6	0.29 0.43	25.8 23.7	0.19 0.24	38.6 36.5
Weibull-2p Weibull-2p - tail	0.23	20.0	0.27 0.27	22.8 23.5	0.21 0.16	33.5 36.5
Weibull-3p Weibull-3p - tail	0.20	23.6	0.27 0.31	24.3 23.8	0.19 0.25	38.0 36.6
Target $x_{0.05}$		18		24		30

Table 6.7. Statistical data (in MPa).

6.2.1.8 Part H – Dynagrade

	M18		M24		M30	
Number of data	23		58		91	
	COV	$x_{0.05}$	COV	$x_{0.05}$	COV	$x_{0.05}$
Non-parametric	0.38	15.7	0.26	22.9	0.21	31.4
Normal Normal - tail	0.37	11.3	0.26	26.5	0.21 0.29	35.6 31.4
LogNormal LogNormal - tail	0.36	15.0	0.31	27.0	0.24 0.46	36.0 31.7
Weibull-2p Weibull-2p - tail	0.38	11.4	0.24	26.5	0.21 0.28	34.4 31.5
Weibull-3p Weibull-3p - tail	0.36	16.1	0.25	27.4	0.21 0.36	35.6 32.0
Target $x_{0.05}$		18		24		30

Table 6.8. Statistical data (in MPa).

6.2.1.9 Part I – Dynagrade

	M18		M24		M30	
Number of data	19		75		103	
	COV	$x_{0.05}$	COV	$x_{0.05}$	COV	$x_{0.05}$
Non-parametric			0.22	25.7	0.20	31.4
Normal Normal - tail			0.22 0.20	25.7 25.3	0.22 0.20	30.5 31.2
LogNormal LogNormal - tail			0.23 0.27	26.9 25.2	0.21 0.32	33.2 31.1
Weibull-2p Weibull-2p - tail			0.22 0.17	24.5 25.3	0.20 0.20	28.6 31.1
Weibull-3p Weibull-3p - tail			0.21 0.31	27.0 25.2	0.20 0.28	33.1 31.2
Target $x_{0.05}$		18		24		30

Table 6.9. Statistical data (in MPa).

6.2.1.10 Part J – Dynagrade

	M18		M24		M30	
Number of data	44		99		55	
	COV	$x_{0.05}$	COV	$x_{0.05}$	COV	$x_{0.05}$
Non-parametric	0.25	21.1	0.23	25.0	0.21	26.2
Normal Normal - tail	0.25	19.1	0.23 0.24	25.7 24.6	0.21	32.3
LogNormal LogNormal - tail	0.23	21.3	0.25 0.35	26.8 24.7	0.24	32.3
Weibull-2p Weibull-2p - tail	0.28	16.6	0.23 0.22	24.3 24.6	0.21	31.2
Weibull-3p Weibull-3p - tail	0.24	20.9	0.23 0.28	26.1 24.8	0.21	32.2
Target $x_{0.05}$		18		24		30

Table 6.10. Statistical data (in MPa).

6.2.1.11 All data - Dynagrade

	M18		M24		M30	
Number of data	218		819		725	
	COV	$x_{0.05}$	COV	$x_{0.05}$	COV	$x_{0.05}$
Non-parametric	0.31	21.1	0.28	24.6	0.23	32.6
Normal	0.31	15.1	0.28	22.8	0.23	33.2
Normal – tail	0.25	17.2	0.24	24.6	0.22	33.3
LogNormal	0.32	17.7	0.30	25.0	0.24	34.7
LogNormal - tail	0.37	17.2	0.35	24.4	0.32	33.0
Weibull-2p	0.33	14.2	0.30	20.9	0.24	30.9
Weibull-2p - tail	0.23	17.3	0.21	24.6	0.20	33.2
Weibull-3p	0.31	15.9	0.29	21.6	0.23	33.2
Weibull-3p - tail	0.27	17.2	0.22	24.5	0.25	33.0
Target $x_{0.05}$		18		24		30

Table 6.11. Statistical data (in MPa).

7 Database H

7.1 Contents of database

Species	Sitka spruce
Number of specimens	Approximately 500
Dimensions	43 x 173 mm and 37 x 103 mm
Origin	The material was collected from Irish sawmills
Loading mode	Bending
Quality	Normal run-of-mill quality
Pre-grading	None
Visual grading	Visual grading at laboratories to Nordic T-rules [1]
Machine grading	None
More information	[10]
Remarks	

7.2 Bending strength

7.2.1 Visual grading

Table 7.1 summarizes the results for visual graded data. The results for tail fits correspond to using 30% of the data. It is seen that

- the 2 parameter Weibull distribution gives the smallest COV (=0.16 – 0.21).
- the LogNormal distribution gives rather large COV's
- the characteristic values are generally larger than the target characteristic values, especially for grading T2.

	T0		T1		T2		T3	
Number of data	173		265		60		15	
	COV	$x_{0.05}$	COV	$x_{0.05}$	COV	$x_{0.05}$	COV	$x_{0.05}$
Non-parametric	0.34	14.8	0.23	21.2	0.19	31.4		
Normal Normal – tail	0.34 0.23	12.1 15.0	0.22 0.23	20.7 20.8	0.18 0.19	29.0 30.1		
LogNormal LogNormal – tail	0.34 0.35	15.0 14.8	0.24 0.34	21.8 20.7	0.19 0.24	30.9 29.2		
Weibull-2p Weibull-2p – tail	0.35 0.21	11.9 14.9	0.24 0.21	19.0 20.8	0.19 0.16	28.6 29.0		
Weibull-3p Weibull-3p – tail	0.34 0.30	14.5 14.8	0.34 0.27	19.5 20.7	0.26 0.20	29.0 29.3		
Target $x_{0.05}$		14		18		24		30

Table 7.1. Statistical data (in MPa).

7.2.2 Machine grading

7.2.2.1 Cook-Bolinder

Table 7.2 summarizes the results for machine graded data by the Cook-Bolinder machine. The results for tail fits correspond to using 30% of the data. It is seen that

- the COV is approximately 0.30, but tail fit with 2 parameter Weibull gives a COV=0.21.
- the characteristic values are smaller than the target characteristic values.

	M18		M24		M30	
Number of data	1		22		386	
	COV	$x_{0.05}$	COV	$x_{0.05}$	COV	$x_{0.05}$
Non-parametric			0.33	16.0	0.29	27.1
Normal Normal - tail			0.32	14.9	0.29 0.23	24.2 26.3
LogNormal LogNormal - tail			0.32	17.7	0.31 0.34	27.0 26.1
Weibull-2p Weibull-2p - tail			0.34	13.9	0.30 0.21	23.1 26.2
Weibull-3p Weibull-3p - tail			0.32	17.6	0.29 0.28	26.1 26.1
Target $x_{0.05}$		18		24		30

Table 7.2. Statistical data (in MPa).

8 Database I

8.1 Contents of database

Species	Norway spruce
Number of specimens	Approximately 500
Dimensions	47 x 173 mm, 44 x 100 and 40 x 100 mm
Origin	The material was collected from French sawmills
Loading mode	Bending
Quality	Normal run-of-mill quality
Pre-grading	None
Visual grading	Visual grading at laboratories to Nordic T-rules [1]
Machine grading	None
More information	[10]
Remarks	

8.2 Bending strength

8.2.1 Visual grading

Table 8.1 summarizes the results for visual graded data. The results for tail fits correspond to using 30% of the data. It is seen that

- the 2 parameter Weibull distribution gives the smallest COV (=0.19 – 0.27).
- the characteristic values are generally larger than the target characteristic values.

	T0		T1		T2		T3	
Number of data	39		194		152		117	
	COV	$x_{0.05}$	COV	$x_{0.05}$	COV	$x_{0.05}$	COV	$x_{0.05}$
Non-parametric	0.36	13.2	0.29	19.7	0.24	24.9	0.19	33.1
Normal Normal - tail	0.35	13.1	0.29 0.28	19.4 19.8	0.24 0.28	27.4 25.7	0.19 0.25	36.6 33.5
LogNormal LogNormal - tail	0.41	15.3	0.32 0.45	21.5 19.6	0.28 0.43	28.1 25.9	0.21 0.35	36.8 33.7
Weibull-2p Weibull-2p - tail	0.35	13.5	0.30 0.27	18.7 19.7	0.24 0.26	26.4 25.8	0.19 0.22	35.2 33.6
Weibull-3p Weibull-3p - tail	0.36	15.3	0.30 0.31	19.8 19.6	0.24 0.29	27.2 25.9	0.18 0.27	36.4 33.9
Target $x_{0.05}$		14		18		24		30

Table 8.1. Statistical data (in MPa).

9 Database J

9.1 Contents of database

Species	Norway spruce
Number of specimens	850
Dimensions	45 x 145 mm
Origin	Swedish sawmill
Loading mode	Bending, compression and tension
Quality	Normal run-of-mill quality below average quality of Swedish grown spruce of 5th appearance grade
Pre-grading	None
Visual grading	Visual grading at laboratories to Nordic T-rules [1]
Machine grading	None
More information	
Remarks	The specimens were tested at a range of moisture contents and the strength values subsequently corrected to the reference condition (65 % RH, 20 °C)

9.2 Bending strength

9.2.1 Visual grading

Table 9.1 summarizes the results for visual graded data. The results for tail fits correspond to using 30% of the data. It is seen that

- the 2 parameter Weibull distribution gives the smallest COV (=0.15 – 0.20).
- the LogNormal distribution gives rather large COV's
- the target characteristic values are compared to the estimated characteristic values smaller than for grading T1, almost equal to for grading T2 and larger than for grading T3.

	T0		T1		T2		T3	
Number of data	13		109		78		78	
	COV	$x_{0.05}$	COV	$x_{0.05}$	COV	$x_{0.05}$	COV	$x_{0.05}$
Non-parametric			0.22	22.0	0.23	25.1	0.19	26.4
Normal			0.22	21.4	0.23	22.9	0.19	28.4
Normal - tail			0.21	21.1	0.18	23.9	0.26	26.0
LogNormal			0.23	22.5	0.23	24.6	0.21	28.9
LogNormal - tail			0.30	21.0	0.24	23.9	0.37	26.3
Weibull-2p			0.23	20.0	0.25	20.8	0.20	26.5
Weibull-2p - tail			0.19	21.1	0.15	23.9	0.23	26.1
Weibull-3p			0.22	22.0	0.32	24.1	0.20	28.2
Weibull-3p - tail			0.28	20.9	0.22	23.9	0.30	26.6
Target $x_{0.05}$		14		18		24		30

Table 9.1. Statistical data (in MPa).

9.3 Compression strength

9.3.1 Visual grading

Table 9.2 summarizes the results for visual graded data. The results for tail fits correspond to using 30% of the data. It is seen that

- the 2 parameter Weibull distribution gives the smallest COV (=0.12 – 0.16).
- the target characteristic values are smaller than the estimated characteristic values, especially for gradings T1 and T2.

	T0		T1		T2		T3	
Number of data	5		86		147		189	
	COV	$x_{0.05}$	COV	$x_{0.05}$	COV	$x_{0.05}$	COV	$x_{0.05}$
Non-parametric			0.17	21.5	0.14	25.2	0.15	28.3
Normal			0.16	21.5	0.22	19.6	0.24	21.8
Normal - tail			0.17	21.3	0.11	25.4	0.15	27.9
LogNormal			0.17	22.1	0.14	25.4	0.15	28.6
LogNormal - tail			0.22	21.3	0.13	25.4	0.19	27.8
Weibull-2p			0.18	19.8	0.09	22.6	0.17	25.8
Weibull-2p - tail			0.14	21.3	0.16	25.4	0.12	27.9
Weibull-3p			0.17	21.4	0.52	21.6	0.15	28.0
Weibull-3p - tail			0.18	21.4	0.12	25.4	0.17	27.8
Target $x_{0.05}$		12		15		20		26

Table 9.2. Statistical data (in MPa).

9.4 Tensile strength

9.4.1 Visual grading

Table 9.3 summarizes the results for visual graded data. The results for tail fits correspond to using 30% of the data. It is seen that

- the COV's are in the range 0.25 0.27.
- the target characteristic values are smaller than or equal to the estimated characteristic values, especially for grading T1.

	T0		T1		T2		T3	
Number of data	6		54		47		32	
	COV	$x_{0.05}$	COV	$x_{0.05}$	COV	$x_{0.05}$	COV	$x_{0.05}$
Non-parametric			0.25	13.5	0.27	14.9	0.22	20.0
Normal Normal - tail			0.25	14.0	0.26	15.6	0.22	19.4
LogNormal LogNormal - tail			0.26	15.1	0.28	16.9	0.22	20.7
Weibull-2p Weibull-2p - tail			0.26	13.0	0.27	14.8	0.25	17.2
Weibull-3p Weibull-3p - tail			0.25	14.6	0.27	16.7	0.22	20.6
Target $x_{0.05}$		8		10		16		20

Table 9.3. Statistical data (in MPa).

10 Database K

10.1 Contents of database

Species	Sitka spruce of Danish origin
Number of specimens	Approximately 700
Dimensions	45 x 145 mm
Origin	The material was collected from two Danish sawmills
Loading mode	Bending and tension
Quality	Normal run-of-mill quality
Pre-grading	None
Visual grading	Visual grading at laboratories to Nordic T-rules [1]. The highest grade T3 is not produced; instead a combined grade consisting of both T2 and T3 is produced and termed T2$^+$
Machine grading	None
More information	[11]
Remarks	

10.2 Bending strength

10.2.1 Visual grading

Table 10.1 summarizes the results for visual graded data. The results for tail fits correspond to using 30% of the data. It is seen that

- the 2 parameter Weibull distribution gives the smallest COV (=0.20 – 0.22).
- the LogNormal distribution gives rather large COV's
- the target characteristic values are much larger than the estimated characteristic values.

	T0		T1		T2 and T3	
Number of data	38		218		201	
	COV	$x_{0.05}$	COV	$x_{0.05}$	COV	$x_{0.05}$
Non-parametric	0.27	16.9	0.24	24.4	0.22	29.1
Normal Normal - tail	0.26	20.9	0.24 0.25	23.5 23.3	0.22 0.23	29.3 28.8
LogNormal LogNormal - tail	0.32	21.3	0.26 0.36	24.7 23.4	0.24 0.32	30.3 28.8
Weibull-2p Weibull-2p - tail	0.27	20.0	0.25 0.22	22.1 23.4	0.23 0.20	27.5 28.9
Weibull-3p Weibull-3p - tail	0.27	20.7	0.24 0.26	23.6 23.5	0.22 0.23	28.9 28.9
Target $x_{0.05}$		14		18		24

Table 10.1. Statistical data (in MPa).

10.3 Tensile strength

10.3.1 Visual grading

Table 10.2 summarizes the results for visual graded data. The results for tail fits correspond to using 30% of the data. It is seen that

- the COV is generally in the interval 0.17 – 0.25.
- the target characteristic values are much smaller than the estimated characteristic values.

	T0		T1		T2 and T3	
Number of data	0		99		100	
	COV	$x_{0.05}$	COV	$x_{0.05}$	COV	$x_{0.05}$
Non-parametric			0.25	16.6	0.18	23.5
Normal Normal - tail			0.25 0.26	17.1 16.2	0.18 0.24	23.9 21.8
LogNormal LogNormal - tail			0.42 0.42	15.5 16.1	0.20 0.34	24.1 21.8
Weibull-2p Weibull-2p - tail			0.25 0.25	16.5 16.1	0.17 0.21	23.5 21.8
Weibull-3p Weibull-3p - tail			0.36 0.42	16.7 16.0	0.17 0.29	24.1 21.9
Target $x_{0.05}$		8		10		16

Table 10.2. Statistical data (in MPa).

11 Reliability aspects

11.1 Stochastic model

The following representative limit state function is considered:

$$g = zRX_R - ((1-\alpha)G + \alpha Q) \qquad (21)$$

where

R	strength
X_R	model uncertainty
z	design variable
G	permanent load
Q	variable load
α	factor between 0 and 1, representing the relative fraction of variable load.

In the reliability analyses shown below the stochastic model in table 11.1 is used. The coefficient of variation for the strength, VR is established on the basis of the statistical results in section 2 to 10. It is noted that the stochastic model in table 11.1 with VR =0.15 has been used to calibrate the partial safety factors in the Danish structural codes, [13] and [15].

Variable	Distribution type	Expected value	COV	Quantile value
Permanent load	N	1	0.10	50 %
Variable load (environmental load)	G	1	0.40	98 %
Variable last (imposed load)	G	1	0.20	98 %
Strength	LN	1	VR	5 %
Model uncertainty	N	1	0.05	50 %

Table 11.1 Stochastic model.

The design variable $z = \max(z_1, z_3)$ is determined from the following two design equations from established from load combination 2.1 (LC 2.1) and load combination 2.3 (LC 2.3) in DS 409, [15]:

LC 2.1: $$z_1 R_c / \gamma_R - \left((1-\alpha)\gamma_{G_1} G_c + \alpha\gamma_{Q_1} Q_c\right) = 0 \qquad (22)$$

LC 2.3: $$z_3 R_c / \gamma_R - \left((1-\alpha)\gamma_{G_3} G_c + \alpha\gamma_{Q_3} Q_c\right) = 0 \qquad (23)$$

Where index c indicates characteristic value and

γ_{G1}	partial safety factor for permanent load in LC 2.1
γ_{Q1}	partial safety factor for variable load in LC 2.1
γ_{G3}	partial safety factor for permanent load in LC 2.3
γ_{Q3}	partial safety factor for variable load in LC 2.3
γ_R	partial safety factor for strength

The partial safety factors used are shown in table 11.2. In DS 409 and DS 413 it is specified that γ_R = 1.5 and 1.64 for VR = 0.15 (glulam timber structures) and 0.20 (other structural timber).

	Partial safety factor	
	LC 2.1	LC 2.3
Permanent load	$g_{G_1} = 1.0$	$g_{G_3} = 1.15$
Variable load (environmental load)	$g_{Q_1} = 1.5$	$g_{Q_3} = 1.0$
Variable last (imposed load)	$g_{Q_1} = 1.3$	$g_{Q_3} = 1.0$
strength	$g_R = g_2$	

Table 11.2. Partial safety factors in DS 409, [15].

11.2 Reliability level for LogNormal distributed strength

Figure 11.1 and 11.2 show the reliability index as function of a for environmental and imposed variable load for (VR, g_R)=(0.15, 1.5) and (0.20, 1.64). For a in the typical interval for timber structures, 0.4 to 0.8, it is seen that the average reliability index for VR = 0.15 is approximately 4.8. This is also the reliability level used in calibration of the partial safety factors in the Danish structural codes, see Sørensen et al. [16].

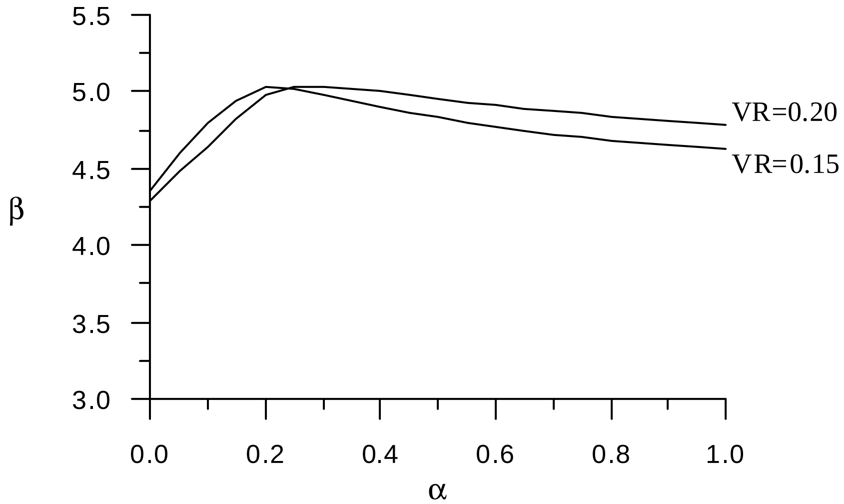


Figure 11.1. Reliability index for environmental load.

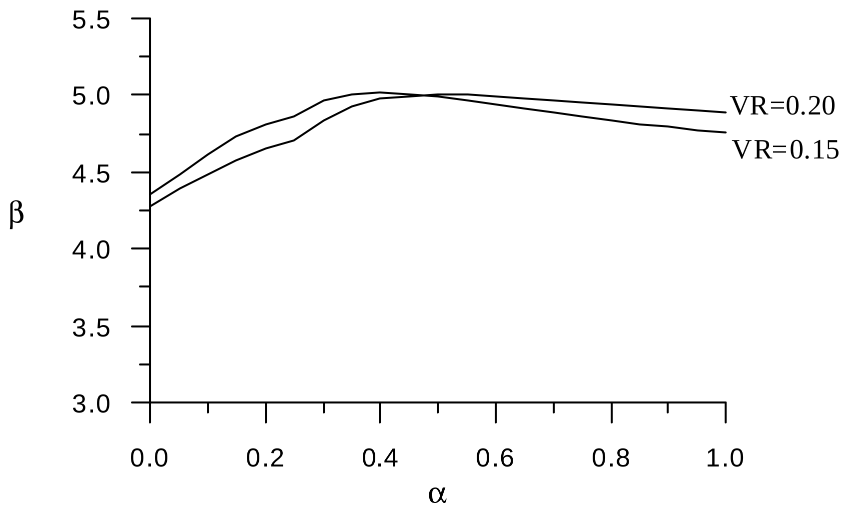


Figure 11.2. Reliability index for imposed load.

11.3 Partial safety factors for LogNormal distributed strength

Figure 11.3 and 11.4 show the partial safety factor g_R for environmental and imposed load as function of a calibrated to give the reliability index b_t=4.8. It is seen that g_R=1.5, 1.6 and 1.7 are reasonable values for a in the interval 0.4 to 0.8 when VR=0.15, 0.20 and 0.25.

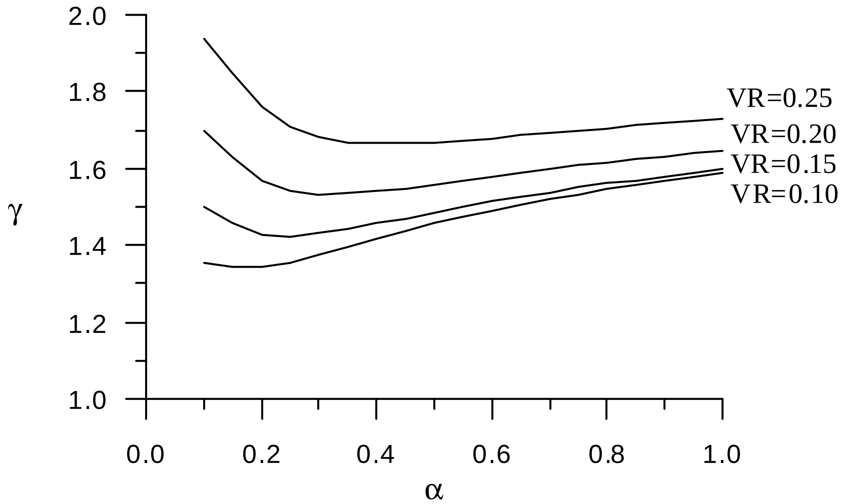


Figure 11.3. Partial safety factor for environmental load and b_t=4.8.

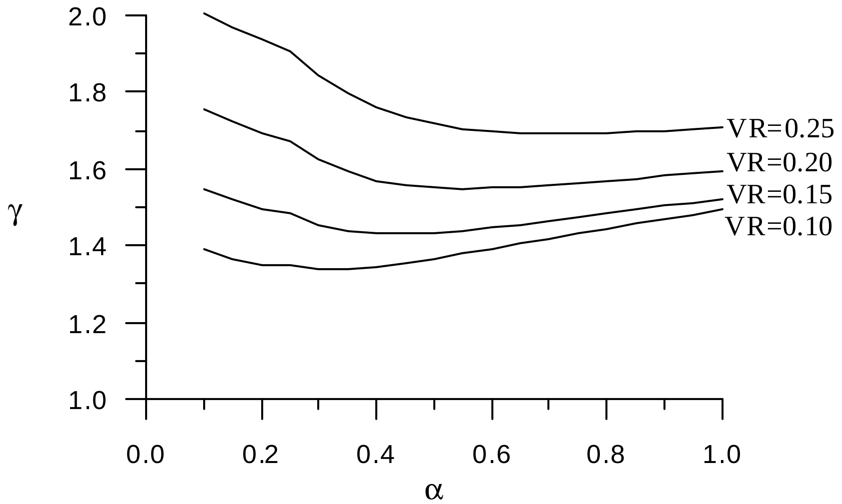


Figure 11.4. Partial safety factor for imposed load and b_t=4.8.

Figure 11.5 and 11.6 show the partial safety factor g_R for environmental and imposed load as function of a calibrated to give the reliability index b_t=4.3 (approximately one safety class lower or equivalently a target annual probability of failure a factor 10 higher). It is seen that g_R=1.3, 1.35 and 1.45 are reasonable values for a in the interval 0.4 to 0.8 when VR=0.15, 0.20 and 1.25.

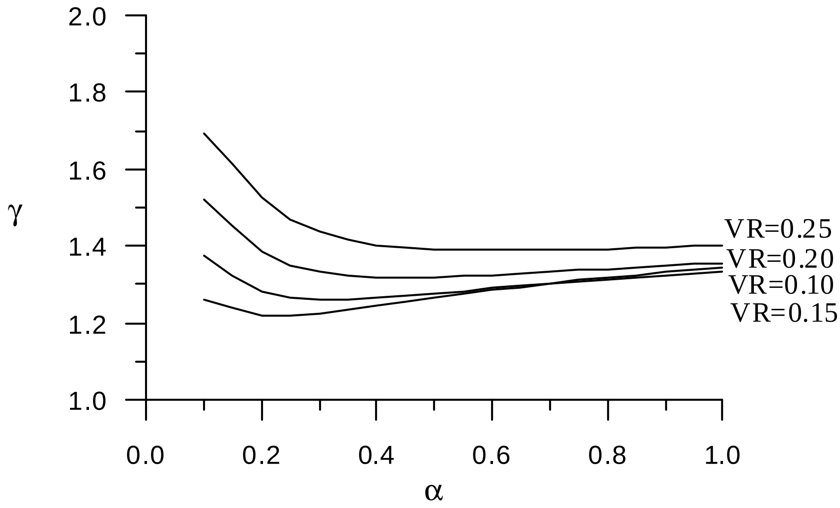


Figure 11.5. Partial safety factor for environmental load and $\boldsymbol{b}_t$ =4.3.

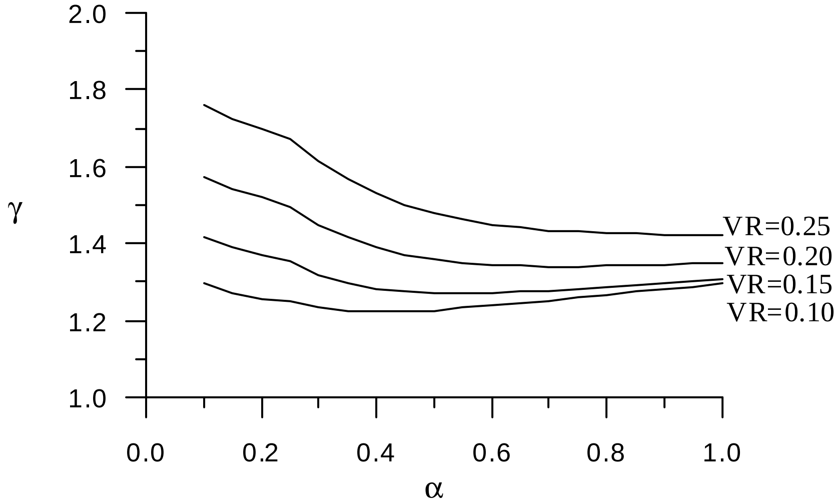


Figure 11.6. Partial safety factor for imposed load and $\boldsymbol{b}_t$ =4.3.

11.4 Reliability level for Weibull distributed strength

Figure 11.7 and 11.8 show the reliability index as function of α for environmental and imposed variable load for (VR, γ_R)=(0.15, 1.5) and (0.20, 1.64). It is noted that the statistical parameters in the 2-parameter Weibull distribution is calibrated such that the same characteristic value as for the LogNormal distributed strength is obtained. For α in the typical interval for timber structures, 0.4 to 0.8, it is seen that the average reliability index is approximately 3.9 for VR=0.15, i.e. significantly lower than for LogNormal distributed material strength.

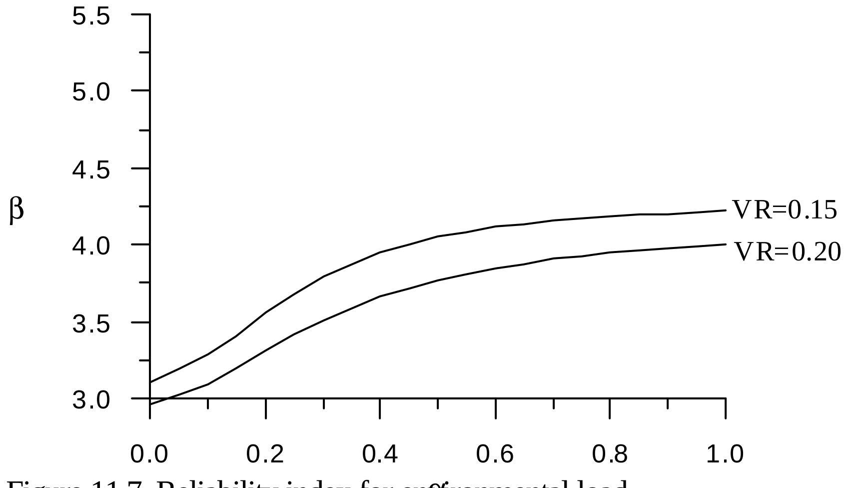


Figure 11.7. Reliability index for environmental load.

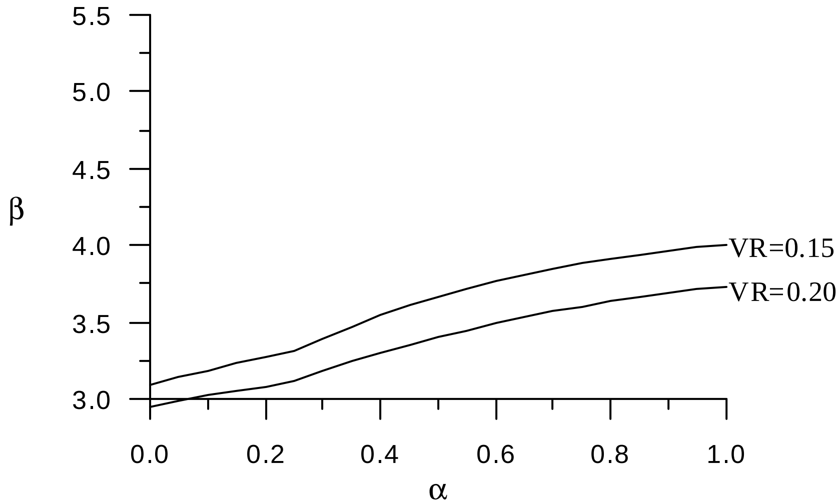


Figure 11.8. Reliability index for imposed load.

11.5 Partial safety factors for Weibull distributed strength

Figure 11.9 and 11.10 show the partial safety factor g_R for environmental and imposed load as function of a calibrated to give the reliability index b_t=3.9. g_R is seen to be approximately equal to 1.5 (as expected) when VR = 0.15, but g_R should be significantly higher than 1.64 when VR = 0.20 in order to obtain the same reliability level.

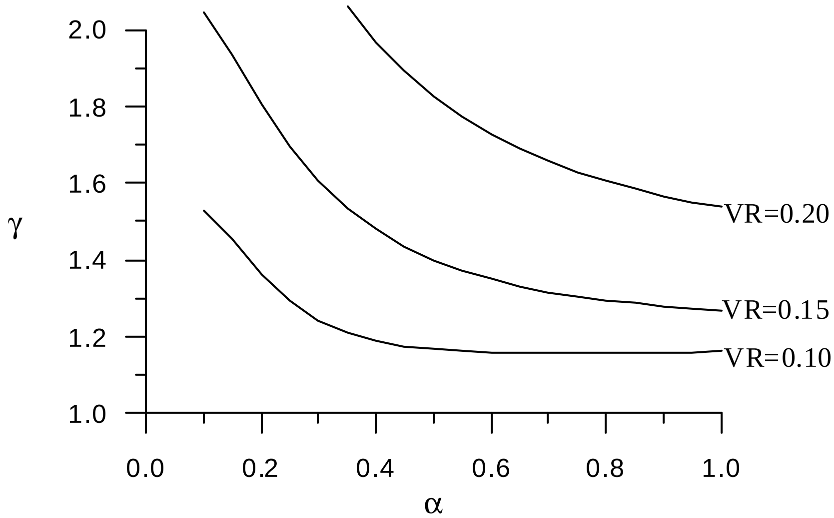


Figure 11.9. Partial safety factor for environmental load.

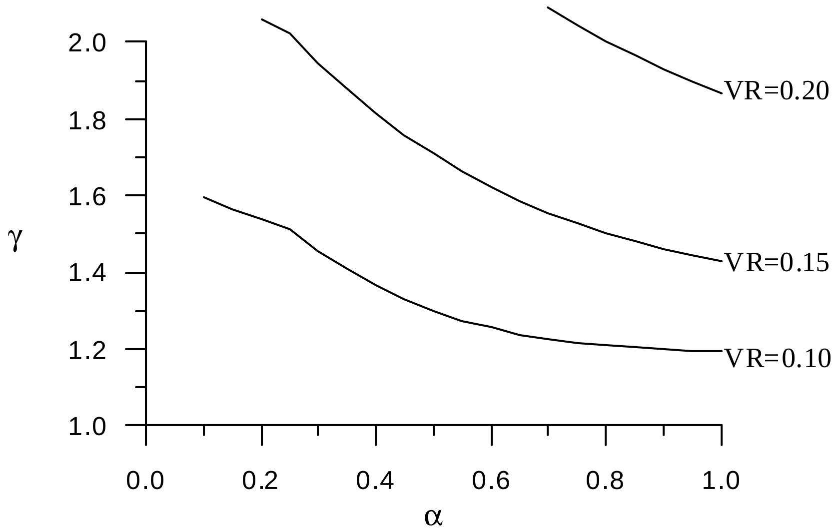


Figure 11.10. Partial safety factor for imposed load.

11.6 Summary of reliability level / partial safety factor aspects

The above results show that

- the reliability level is approximately equal to the reliability level used in calibration of the partial safety factors in the Danish structural codes if the material strength is LogNormal distributed with a coefficient of variation, VR =0.15.
- partial safety factors g_R=1.6 and 1.7 are reasonable values when VR = 0.20 and 0.25 and the strength is LogNormal distributed.

- If the reliability level is chosen to b_t=4.3 (approximately one safety class lower) then partial safety factors g_R=1.3, 1.35 and 1.45 are reasonable when VR=0.15, 0.20 and 0.25 and the strength is LogNormal distributed.
- If the material strength is modeled by a 2-parameter Weibull distribution calibrated such that the same characteristic value as for the LogNormal distributed strength then the average reliability index is approximately 3.9 for VR=0.15, i.e. significantly lower than for LogNormal distributed material strength.
- Using b_t=3.9 for Weibull distributed strengths it is seen that the partial safety factor g_R should be significantly higher than 1.64 when VR = 0.20.

12 Summary / Conclusions

Following the results presented in this report the following observations can be made:

- 2-parameter Weibull (and Normal) distributions give the best fits to the data available, especially if tail fits are used.
- LogNormal distribution generally gives a poor fit and larger coefficients of variation, especially if tail fits are used.

- Bending strengths approximately have a coefficient of variation, COV equal to 20 % if 2-parameter Weibull tail fits are used. If a LogNormal distribution is fitted then the COV is approximately 25%.
- Tension strengths approximately have a coefficient of variation, COV equal to 25 % if 2-parameter Weibull tail fits are used. If a LogNormal distribution is fitted then the COV is approximately 30%.
- Compression strengths approximately have a coefficient of variation, COV equal to 15 % if 2-parameter Weibull tail fits are used. If a LogNormal distribution is fitted then the same COV is obtained.
- It seems thus reasonable to introduce different partial safety factors for bending, tension and compression strength.

- COV generally decreases for higher strength classes
- There is no significant difference in COV's obtained by visual grading and machine grading.

- Characteristic values (5 % quantiles) varies significantly compared to 'target' values. Generally, visual grading gives larger estimated values than target values and Dynagrade machine grading gives slightly larger estimated values than target values. Grading by the Cook-Bolinder and Computermatic machine gives lower estimated values than target valuesAlthough influenced by dimensions and grading speed, the latter results warrant a reconsideration of machine settings, particularly for thin dimensions.

- The reliability investigations show that if the same reliability level is used as in the Danish structural codes from 1998, then partial safety factors g_R = 1.5, 1.6 and 1.7 are reasonable values for COV = 0.15, 0.20 and 0.25 when the strength is LogNormal distributed.
- If the strength is modeled by a 2-parameter Weibull distribution then the reliability level is significantly lower. Higher partial safety factors has to be used for COV's equal to 0.20 and 0.25 compared to those for LogNormal distributed strengths.

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