STRENGTH OF GLUED LAMINATED BEAMS

PART 4

H. J. LARSEN & H. RIBERHOLT
TENSILE STRENGTH PERPENDICULAR TO THE GRAIN
AUGUST 1981

ISSN 0105-7421 REPORT NO. 8110
Dean,
Institute of Building Technology and Structural Engineering,
AALBORG Universities Center,
Auc, AALBORG,
Denmark. 10th. Jan. 1993

Dear Sir,

Enquireis on Research Paper

I am a research scholar in University Technology of Malaysia. I have also registered as a master student as well. Currently, my supervisor, Dr. Zainai, and I have come across an article that published by your institute. We found some of our interest in the paper regarding "Strength of Glued Laminated Beams (Part 5)". Unfortunately, the reading is terminated due to the incomplete printing and missing pages.

We would be grateful if you can do us a favor by sending the following papers:-

(i) Strength of Clued Laminated Beams (Part 5). Report No. 8201
We are looking forward to correspond with your institute in the future, since we share some similar interest in the research of glued laminated timber structures.

Thank you.

Yours Sincerely,

(Chang Chee Wei)
Research Scholar,
Department of Structural and Materials,
Faculty of Civil Engineering,
University Technology of Malaysia,
Karung Berkunci 791,
80990 Johor Bharu,
Johor, Malaysia.
Mr. Chang Chee Wei
Department of Structural and Materials
Faculty of Civil Engineering
University Technology of Malaysia
Karung Berkunci 791
80990 Johor Bharu
Johor, Malaysia

Dear Mr. Chang Chee Wei,

Thank you for your letter dated 10th January 1993 regarding research papers.
Unfortunately the reports you refer to in your letter are not in stock any longer. We do not even have a copy left of 8004. Therefore I can only send you copies of no. 8201 and 8110. I hope you can make use of them.

Do not hesitate to contact us in the future. We would be interested in hearing more about your research activities.

Yours sincerely,

Lambert Mortensen
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1. INTRODUCTION

The tensile strength perpendicular to the grain can in some cases determine the load-carrying capacity of a timber structure. Especially the structure shown in figure 1 has received attention after a number of collapses in the period 1965-1970.

Figure 1. Pitched cambered curved beam.

Methods for calculating the stresses in the curved part of the beam were set up by [Foschi, 1970], [Foschi et al., 1970], [Fox, 1974a], and the strength parameters were determined: [Madsen, 1972], [Fox, 1974b] and [Barrett et al., 1975].

The resulting design rules, e.g. [CIB, 1980] are based on strength and stiffness parameters for North American wood species, and they might be too restrictive for structures of European softwoods.

For these species the stress distribution has been investigated by Riberholt [Riberholt, 1981], and the present paper gives the results of tests to determine the short-term tensile strength perpendicular to the grain and its dependence on volume. The tests have been made at the Department of Structural Engineering, Technical University of Denmark, 1) and at the Institute of Building Technology and Structural Engineering, Aalborg University Centre 2).

1) where H. Riberholt is employed and where series 2 was tested (see section 2).
2) where H. J. Larsen was employed and where series 1 was tested.

The test materials have been supplied by the glulam factories Lami Limtræ, Limfjordstræ, Limtræ Lilleheden and LNJ spændtræ.

The investigation has been supported by a grant from Statens teknisk-videnskabelige Forskningsråd (Danish Council for Scientific and Technical Research).

2. TEST MATERIALS

Table 2a. Approximate dimensions of specimens.

<table>
<thead>
<tr>
<th></th>
<th>b</th>
<th>c</th>
<th>h</th>
<th>Volume 10^-3 m³</th>
</tr>
</thead>
<tbody>
<tr>
<td>Series 1</td>
<td>90</td>
<td>97</td>
<td>300</td>
<td>2.62</td>
</tr>
<tr>
<td>Series 2</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>type 1</td>
<td>139</td>
<td>141</td>
<td>1336</td>
<td>26.2</td>
</tr>
<tr>
<td>2</td>
<td>139</td>
<td>141</td>
<td>128</td>
<td>2.51</td>
</tr>
<tr>
<td>3</td>
<td>90</td>
<td>97</td>
<td>294</td>
<td>2.57</td>
</tr>
<tr>
<td>4</td>
<td>45</td>
<td>46</td>
<td>133</td>
<td>0.275</td>
</tr>
<tr>
<td>5</td>
<td>20</td>
<td>20</td>
<td>67</td>
<td>0.0268</td>
</tr>
</tbody>
</table>

Two series were tested. The purpose of series 1 was to determine the distribution of the tensile strength perpendicular to the grain for the wood normally used in Denmark (and the other Nordic countries) for glued laminated structures, i.e. Nordic whitewood (Picea abies). The purpose of series 2 was to determine the dependence on volume of the tensile strength.

The dimensions of the specimens are given in table 2a.

Figure 2b. Cutting of specimens for series 2. Measurements in mm. The grain direction is indicated by →. 
Series 1
Each of three factories delivered approximately 30 cut-offs from their normal beam production, i.e. with different widths (minimum 90 mm) and depths (minimum 367 mm). The laminal thickness was app. 33 mm. Test specimens with the dimensions given in table 2a were cut from the blocks.

Series 2
All specimens were cut from one beam as shown in figure 2b. All cuts parallel to the glue lines were made in the middle of a lamina, making the glue line area proportional to the volume. Type 3 corresponded to series 1 and type 2 and 3 had the same volume but different dimensions. The volume of series 2 covered three decades, see table 2a.

3. TESTING
The dimensions, the annual ring width, the weight of the specimens, and the moisture content were determined the last-mentioned property either by drying and reweighing or by a calibrated electric moisture-meter (Delmhorst).

Steel plates were glued to the end surfaces with PVAC-glue. The load was transferred by threaded rods screwed into the centre of the steel plates, see figure 3a-c. The steel plates were so thick that their deformations were negligible, and the rods so thin that yielding secured that no moments were transferred.

The load was increased at a constant speed until failure. The time to failure was 3-5 min. During loads up to 25-30 per cent of the failure load the elongations were measured over a length of 100 mm with gauges placed in the middle of the sides parallel to the grain direction. (No measurements were made for the shortest specimens, type 5).

Figure 3a. Test set up.

Figure 3b-c. Test set up. Series 2, type 1.
4. TEST RESULTS

The main test results are summarized in table 4a.

The moisture content was rather uniform. For series 1 it varied between 0.105 and 0.135. For series 2 the variation was from 0.08 - 0.12 with only a few results outside the range 0.085 - 0.105, and with a difference of less than 0.005 between the laminae adjacent to the failure surface. Consequently, no corrections of the test results have been made.

The specific density corresponds to dry weight and volume at the actual moisture content. The density is based on the weight of the whole specimen except for series 2, type 1, where the density was determined for the laminae adjacent to the failure surface.

The annual ring width given is the bigger of the values for the laminae containing or adjacent to the failure surface. The coefficient of variation was 30-50 per cent.

The failure surfaces were approximately cylindrical with the axis parallel to the grain. Typical failure surfaces are shown in figure 4b-d.

As seen from the figures many of the failures are close to a glue line, but failure in the glue line occurred very seldom and only partly.

The failure occurred in the glue line between wood and steel for
- series 1, partly (max. 25 per cent) in four cases out of 87,
- series 2, type 4 in 10 cases out of 18,
- series 2, type 5 in 15 cases out of 36.

The tensile strength measured for these specimens are thus lower than the actual values.

The modulus of elasticity was calculated from the average of the two measured elongations. They often differed substantially, a ratio of 1:2 was not unusual. It was ascertained that this was not due to the test set-up. When the ratio between the two elongations was more

<table>
<thead>
<tr>
<th>Number of specimens</th>
<th>Specific density</th>
<th>Annual ring width</th>
<th>Tensile strength $f_L$, MPa</th>
<th>Modulus of elasticity, $E_{90}$, MPa</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>mean</td>
<td>c.o.v.</td>
<td>mean</td>
<td>c.o.v.</td>
</tr>
<tr>
<td><strong>Series 1</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Factory 1</td>
<td>26</td>
<td>0.44</td>
<td>3</td>
<td>2.3</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>0.42</td>
<td>4</td>
<td>2.8</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>0.42</td>
<td>3</td>
<td>2.3</td>
</tr>
<tr>
<td></td>
<td>1-3</td>
<td>0.43</td>
<td>5</td>
<td>1.092</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>0.58</td>
<td></td>
<td>0.58</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>370</td>
<td>28</td>
<td>370</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>370</td>
<td>23</td>
<td>360</td>
</tr>
<tr>
<td><strong>Series 2</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Type 1</td>
<td>18</td>
<td>0.44</td>
<td>5</td>
<td>2.1</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>0.46</td>
<td>11</td>
<td>2.4</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>0.44</td>
<td>3</td>
<td>1.9</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>0.44</td>
<td>3</td>
<td>1.9</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>0.42</td>
<td>6</td>
<td>1.6</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>490</td>
<td>17</td>
<td>490</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>530</td>
<td>20</td>
<td>530</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>240</td>
<td>21</td>
<td>240</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>120</td>
<td>360</td>
<td>120</td>
</tr>
</tbody>
</table>
than 1.25 the specimens were carefully examined. In two specimens (series 1) cracks were found and the specimens were rejected. In series 2 the biggest differences between the elongations were found for specimens type 4 and especially type 3.

![Figure 4d. Specimens series 2, type 4 after testing.](image)

5. DISCUSSION OF TEST RESULTS

No correlation was found between the tensile strength and the following variables: Modulus of elasticity, density and annual ring width.

For series 1 the means of the tensile strength are significantly different on a 99 per cent level. Nevertheless, all the results are in some cases combined in the following, since the user's main interest is the properties of the total population.

By the evaluation of the test results for series 2 the influence of the different annual ring pattern should be taken into account.

The test specimens type 1 and 2 had a pattern as shown in figure 5a, i.e. almost symmetrical about a vertical plane. A calculation based on the assumption that wood is a cylindrical orthotropic material and an angle between the annual rings and the glue line of 10-15° at the surface shows that the stresses at the surface are only half of the stresses in the centre.

![Figure 5a. Annual ring pattern and stress distribution in specimens in series 1 and 2, type 1 and 2.](image)

A similar calculation for the specimens type 3, 4, and 5 shows a more uniform stress distribution, especially for type 5. Thus, if the failure is triggered at the stress peaks specimens type 3, 4, and 5 will have relatively higher strengths than comparable specimens with a pattern as shown in figure 5a.

Table 5c gives in addition to the mean and standard deviation for the tensile strength, i.e. the parameters $\mu$ and $\sigma$ in the normal distribution, the estimates for the parameters in a log-normal, a 2-parameter and a 3-parameter Weibull distribution.

All estimates except for the 3-parameter Weibull distributions are based on maximum likelihood. For the 3-parameter Weibull distribution the parameters are estimated as described in [Pierce, 1976]. It is here utilized that if $f_t$ is Weibull distributed the points

$$(x, y) = (\ln f_t - e), \ln(1 - \frac{1}{N + 1})$$

should fall on a straight line (a Weibull plot). $N$ is the number of data, $i$ the rank.

By the log-normal distribution it is assumed that $\ln f_t$ is normal-distributed with mean $\alpha$ and standard deviation $\beta$. In table 5c $\alpha$ and $\beta$ are given.

The 3-parameter Weibull distribution function is

$$F(x) = \begin{cases} 0 & (x \leq e) \\ 1 - \exp\left[-\left(\frac{x - e}{\delta}\right)^\eta\right] & (x > e) \end{cases}$$

where

- $\eta$ is shape parameter
- $\delta$ is scale parameter
- $e$ is location parameter
- $e (> 0)$ is the minimum possible value. For the 2-parameter Weibull distribution $e = 0$ is assumed.

It is notable that the values for type 2 and 3 are so alike. They have the same volume, but the pattern of annual rings differ, see below.

The difference in methods explains why the parameters in the 2- and 3-parameter distributions are not the same.
Table 5c. Tensile strength. Parameters in different distribution functions.

<table>
<thead>
<tr>
<th></th>
<th>Normal</th>
<th></th>
<th>Log-normal</th>
<th></th>
<th>2-parameter Weibull</th>
<th></th>
<th>3-parameter Weibull</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>mean</td>
<td>stand.dev.</td>
<td>mean</td>
<td>stand.dev.</td>
<td>shape</td>
<td>scale</td>
<td>shape</td>
<td>scale</td>
</tr>
<tr>
<td></td>
<td>(MPa)</td>
<td>(MPa)</td>
<td>(MPa)</td>
<td>(MPa)</td>
<td>(MPa)</td>
<td>(MPa)</td>
<td>(MPa)</td>
<td>(MPa)</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Series 1</td>
<td>Factory 1</td>
<td>0.902</td>
<td>0.179</td>
<td>0.885</td>
<td>1.23</td>
<td></td>
<td>5.71</td>
<td>0.975</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>1.064</td>
<td>0.223</td>
<td>1.042</td>
<td>1.23</td>
<td></td>
<td>5.13</td>
<td>1.155</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>1.292</td>
<td>0.312</td>
<td>1.250</td>
<td>1.32</td>
<td></td>
<td>4.89</td>
<td>1.410</td>
</tr>
<tr>
<td></td>
<td>1-3</td>
<td>1.092</td>
<td>0.289</td>
<td>1.054</td>
<td>1.31</td>
<td></td>
<td>4.04</td>
<td>1.202</td>
</tr>
<tr>
<td>Series 2</td>
<td>Type 1</td>
<td>0.625</td>
<td>0.059</td>
<td>0.622</td>
<td>1.10</td>
<td></td>
<td>12.28</td>
<td>0.663</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>0.997</td>
<td>0.312</td>
<td>0.951</td>
<td>1.38</td>
<td></td>
<td>3.59</td>
<td>1.230</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>1.036</td>
<td>0.330</td>
<td>0.980</td>
<td>1.43</td>
<td></td>
<td>3.61</td>
<td>1.173</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>1.872</td>
<td>0.447</td>
<td>1.813</td>
<td>1.31</td>
<td></td>
<td>4.98</td>
<td>2.082</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>2.381</td>
<td>0.471</td>
<td>2.338</td>
<td>1.21</td>
<td></td>
<td>5.12</td>
<td>2.626</td>
</tr>
</tbody>
</table>

in the cases where $\epsilon = 0$. According to Pierce the 2-parameter distribution gives a safe estimate of the low percentiles e.g. the 5-percentile. The 3-parameter often gives an unsafe estimate.

Figures 5d - 5f show Weibull plots together with the best fit. A Kolmogorov-Smirnov test of goodness showed for series 2 for all sets of parameters a significance level of at least 0.2, i.e. the fit is fairly good.

The lower 5-percentiles of $f_t$ (i.e. the characteristic strengths according to [CIB, 1980]) were estimated according to each of the above-mentioned four distributions. The values are given in table 5g. The combined results for series 1 are put in brackets to indicate that the means of series 1 and 3 are statistically different.

The Weibull distributions are often associated with a brittle fracture theory. This theory predicts that the strength is dependent on volume. Assuming the 2-parameter distribution the following relationship is valid for all percentiles for two volumes $V_1$ and $V_2$ with the same stress distribution (in this case a homogeneous tensile stress distribution).

![Figure 5d. Test series 1, all data, $\epsilon = 0.30$.](image)

![Figure 5e. Test series 2, type 1, $\epsilon = 0.36$.](image)
Figure 5f. Test series 2, type 3, $\varepsilon = 0$.

$$\frac{f_{t,1}}{f_{t,2}} = \left(\frac{V_2}{V_1}\right)^{1/\eta}$$

$f_{t,1}$ and $f_{t,2}$ are the strength values for volume $V_1$ and $V_2$, respectively. Reference is made to e.g. [Barrett, 1974].

According to this theory the parameter $\eta$ which in table 5g was estimated for each type with constant volume, may also, as shown in figure 5h, be estimated by plotting $\log f_t$ versus $\log V$ and fitting a straight line. The slope of the line is $-1/\eta$.

A linear regression was carried out for the mean values (correlation coefficient $= -0.99$) and the 5-percentiles (correlation coefficient $= -0.93$). The values of $1/\eta$ are shown in figure 5h. They correspond to $\eta = 5.10$ (mean) and $\eta = 5.47$ (5-percentile).

Table 5g. Tensile strength $f_t$, 5-percentiles in MPa.

<table>
<thead>
<tr>
<th></th>
<th>Normal log-normal</th>
<th>Weibull 2-parameter</th>
<th>Weibull 3-parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Series 1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Factory 1</td>
<td>0.61 0.63</td>
<td>0.58 0.60</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>0.70 0.74</td>
<td>0.65 0.71</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>0.78 0.79</td>
<td>0.77 0.67</td>
<td></td>
</tr>
<tr>
<td>1-3</td>
<td>(0.62) (0.68)</td>
<td>(0.58) (0.63)</td>
<td></td>
</tr>
<tr>
<td>Series 2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Type 1</td>
<td>0.53 0.53</td>
<td>0.52 0.52</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>0.48 0.56</td>
<td>0.49 0.54</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>0.49 0.54</td>
<td>0.52 0.43</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>1.14 1.16</td>
<td>1.15 1.04</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>1.61 1.70</td>
<td>1.47 1.63</td>
<td></td>
</tr>
</tbody>
</table>

Figure 5h. Series 2, log$f_t$ ($f_t$ in MPa) versus log$V$ ($V$ in mm$^3$).

The values for the shape parameter found from each specimen type gave rather different values - ranging from 3.6 to 12.3 - anyhow the mean and the weighted mean value is 5.9 and 5.8, respectively.

If the test is to be utilized for the prediction of the strength in glulam beams, only the results for specimens with a normal annual ring pattern should be used, cf. figure 5a-b, i.e. type 1, 2, and perhaps 3. For these three specimen types the estimate of $\eta$ are shown in table 5i.

So far it has been assumed that the tensile strengths of different specimens were uncorrelated, but this is not the case. For series 2 specimens type 1 and perhaps 2, the results are influenced by a single weak lamina, lamina No. 29 from the top: 9 of the 18 specimens type 1 and 4 of the 18 specimens type 2 failed in this lamina. The hypothesis that the laminae are of equal strength can be rejected with a significance level calculated by the binomial distribution larger than $1 - 10^{-6}$.

Out of the test specimens of type 1, which did not fail in lamina 29, specimens with the geometry as type 2 and containing lamina 29 were cut and tested in tension.

By pooling all the results from lamina No. 29 in type 1 and 2, the parameters in a 2-parameter Weibull distribution may be estimated. A value of the shape parameter $\eta$ of 4.8 was found.

Table 5i. Estimates of the shape parameter $\eta$ in the 2-parameter Weibull distribution based on type 1, 2 and 3 in series 2.

<table>
<thead>
<tr>
<th>Estimate based on</th>
<th>$\eta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant volume specimens</td>
<td>6.5</td>
</tr>
<tr>
<td>Strength-volume relationship</td>
<td></td>
</tr>
<tr>
<td>mean (coefficient of correlation = $-1.00$)</td>
<td>4.8</td>
</tr>
<tr>
<td>5-percent. (coefficient of correlation = $-0.68$)</td>
<td>0.0</td>
</tr>
</tbody>
</table>
It can be shown that the percentiles in the strength distribution for specimens with a single weak lamina and of different lengths $L_1$ and $L_2$ are related by the formula

$$f_{t,1} / f_{t,2} = \left( \frac{L_2}{L_1} \right)^{1/n} = \left( \frac{V_2}{V_1} \right)^{1/n}$$

Since the estimate of the shape parameter is almost the same as found previously the strength dependence on volume can in practice be described by the above formula, no matter whether or not a significant weak lamina occurs.

The variation of the modulus of elasticity perpendicular to the grain $E_{90}$ for series 1 and each of the types in series 2 corresponded to a coefficient of variation of 20 per cent.

In series 1 there was no difference between the three factories. The mean value was 365 MPa.

In series 2 $E_{90}$ was much lower for type 3 and 4 than for type 1 and 2. The reason for this is undoubtedly the differences in the pattern of the annual rings, see figure 5a - 5b. Only the $E_{90}$-values for type 1 and 2 are appropriate for the calculation of glulam beams. The mean value for the two types is 510 MPa. The wood quality for series 2 has been tested in other relations and it is estimated that the modulus of elasticity parallel to the grain is about 12500 MPa.

6. CONCLUSIONS

The properties in tension perpendicular to the grain of the qualities of Nordic spruce normally used for untreated glued laminated structures (specific density about 0.45) were investigated.

Two series were tested. In series 1 cut offs from three glulam factories (30 specimens from each) were used and the test specimens had all a volume of $2.7 \cdot 10^{-3}$ m$^3$. In series 2 test specimens with different volumes were tested (max: $2.7 \cdot 10^{-2}$, min: $2.7 \cdot 10^{-5}$ m$^3$), and all specimens were cut from one glulam beam.

The results from series 2 with different volumes are influenced by the variation in annual ring pattern and may be influenced by one or two laminae with low strength values. The investigation should therefore be continued with blocks of different dimensions more typical for the normal production.

The following conclusion can, however, be drawn:

The mean value of the short-term tensile strength perpendicular to the grain $f_t$ for a volume of $2.7 \cdot 10^{-3}$ m$^3$ was 1.05 MPa, and the 5-percentile about 0.55 MPa.

The dependence of $f_t$ on volume may be described by a brittle fracture theory corresponding to a 2-parameter Weibull distribution with a shape parameter of about 5.

The characteristic short-term tensile strength as defined in [CIB, 1980] - i.e. the 5-percentile corresponding to a volume of 0.02 m$^3$ - may thus be estimated at 0.35-0.4 MPa.

The mean value of the modulus of elasticity perpendicular to the grain was 365 MPa in series 1 and 510 MPa in series 2. The latter value corresponds to $E_0/25$ where $E_0$ is the modulus of elasticity parallel to the grain.

7. LITERATURE

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