Strength and Stiffness of Glued Laminated Timber Beams

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Artikkelen beskriver en eksperimentell undersøkelse av linse laminerte trebjelkers styrke og stivhet. I alt ble 47 bjelker belastet til brudd. Bjelkene ble fremstilt av norsk granvirk som ble sortert etter reglene i NS 447. Til alle bjelker ble det benyttet virke av to kvaliteter, med laveste kvalitet i de indre 60% av tverrsnittet. Det ble benyttet tre forskjellige lamelltykkler, nemlig 3/4", 1" og 2".

Det ble påvist en signifikant forskjell i styrke og stivhet mellom laveste og høyeste virkekvalitet. Variasjonene i styrke og stivhet som funksjon av lamelltykkelsen var ikke signifikant, men 2" lameller ga i gjennomsnitt de svakeste bjelkene. Bjelkene styrkeegenskaper var sterkt avhengig av kvaliteten av virket i de ytre lameller på strekkside. Svake angrep av råte eller spor av tennar syntes å kunne medføre sterkt redusert styrke. Kvister som lå så nær kanten av lamellene at fiberforstyrrelserne rundt dem var beskadiget av sagsnittet, var ofte en direkte årsak til brudd. De strengere krav som NS 447 stiller til kvister nær kanten, synes således fornuftige også for virke til laminerte konstruksjoner.

I artikkelen sammenlignes de oppnådde resultater med tilsvarende verdier funnet av Thunell for massive trebjelker av svensk furuvirk, samt med de tillatte verdier som er angitt i NS 446. De laminerte bjelkene var i gjennomsnitt ca. 25 % sterkeere og stivere enn de massive furubjelkene. De tillatte bøyningspenningene som er foreskrevet i NS 446, synes rimelige, men kan trolig forhøyes noe for virke av laveste kvalitet (T 210).

Forsøkene synes å indikere at elastisitetsmodulen for laminerte bjelker av alle virkekvaliteter kan settes ca. 20% høyere enn foreskrevet i NS 446.

1. Introduction.

Glued laminated timber is receiving increasing attention from architects and structural engineers as an attractive material for many types of structures.

In Norway, laminated timber structures are designed in accordance with the provisions of the Norwegian Standard NS 446 (1) issued in 1957, and the materials used for lamination are graded according to the structural grading rules set forth in NS 447 (2).

NS 446 and NS 447 are to a large extent based upon test results from other countries. It was therefore deemed necessary to investigate their adequacy to Norwegian species.

This report presents the results of an experimental investigation of the strength and the stiffness of glued laminated beams. Major variables were grades of timber and thicknesses of laminations.

2. Acknowledgement.

This investigation was carried out as a cooperative research project of the Norwegian Building Research Institute and the Norwegian Institute of Wood Working and Wood Technology. The investigation was sponsored by the Royal Norwegian Council for Scientific and Industrial Research.

![Fig. 1. Nominal dimensions of beams.](image-url)
A total number of 47 laminated beams were tested to destruction. The beams all had a nominal size of 7 × 20 × 450 cm, and were loaded through concentrated loads at the third-points with a total span length of 420 cm, see Fig. 1.

Fig. 2 shows the cross-sections of the beams. Three different series of tests were executed, according to the following scheme:

Series 0; 13 laminations of 16 mm thickness in each beam
Series 1; 9 - 22 B -
Series 2; 4 % -

Each beam consisted of two different grades of timber with the best grade in the outer 20 per cent of the laminations on each side. The Norwegian design specifications state that the allowable bending stresses prescribed for the structural grade which is used in the outer 20 per cent on each side of the cross section can be used even if the inner 60 per cent of the cross section consists of materials of the next lower structural grade.

The structural grading rules of NS 447 are briefly reviewed in Section 5. According to these rules, the timber is classified into the following groups:

T'390, T 300, T 210 or shallower grades, where T 390 represents the highest quality.

Table 1 shows the number of beams which were tested in each of the four major groups of grade combinations. The following symbols are introduced:

<table>
<thead>
<tr>
<th>Grading</th>
<th>Series 0</th>
<th>Series 1</th>
<th>Series 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>AB</td>
<td>6</td>
<td>1</td>
<td>4</td>
</tr>
<tr>
<td>AD</td>
<td>6</td>
<td>1</td>
<td>4</td>
</tr>
<tr>
<td>BC</td>
<td>6</td>
<td>1</td>
<td>4</td>
</tr>
<tr>
<td>CD</td>
<td>6</td>
<td>1</td>
<td>4</td>
</tr>
<tr>
<td>Total</td>
<td>24</td>
<td>4</td>
<td>12</td>
</tr>
</tbody>
</table>

Table 1 contains 42 beams. The remaining five had combinations of grades which fell outside the outlined pattern.

The beams are designated according to the grade combinations in such a way that the first letter indicates the grade of the outer laminations while the second letter denotes the grade of the inner laminations. The first number indicates the series to which the beam belongs. Hence, the number 1 AB 4 identifies beam number 4 of series 1 which had a combination of T'390 and T 300 materials.


Norway spruce from the district of Kirkener in Solør was used in all beams. Kirkener belongs to one of the best forest districts of Norway and is situated approximately 110 meters above sea level at a latitude of 61.3°. The materials were selected at random from a sawmill in the district, and were kilndried from green condition down to a moisture content of 12 % as soon as possible after the sawing.

The structural grading rules of NS 447 are summarized in Table 2. Additional requirements are given in NS 447 for the maximum admissible sum of knots, which is measured over a length of the piece equal to its width but not exceeding 15 cm. Measured in relation to the width of the pertinent face of the piece under consideration.

Table 2. Grading Rules (NS 447)

<table>
<thead>
<tr>
<th>Quality Class</th>
<th>T 390</th>
<th>T 300</th>
<th>T 210</th>
</tr>
</thead>
<tbody>
<tr>
<td>Width of growth rings (mm) max</td>
<td>3</td>
<td>1</td>
<td>--</td>
</tr>
<tr>
<td>Slope of grain</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Narrow face of plank max</td>
<td>1/4</td>
<td>1/3</td>
<td>1/2</td>
</tr>
<tr>
<td>Wide face of plank or board middle portion max</td>
<td>1/4</td>
<td>1/3</td>
<td>1/2</td>
</tr>
<tr>
<td>Wide face of plank or board outer portions max</td>
<td>1/8</td>
<td>1/6</td>
<td>1/4</td>
</tr>
</tbody>
</table>

*) Measured in relation to the width of the pertinent face of the piece under consideration.
3. Outline of tests.

A total number of 47 laminated beams were tested to destruction. The beams all had a nominal size of $7 \times 20 \times 450$ cm, and were loaded through concentrated loads at the third-points with a total span length of 420 cm, see Fig. 1.

Fig. 2 shows the cross-sections of the beams. Three different series of tests were executed, according to the following scheme:

Series 0: 13 laminations of 16 mm thickness in each beam
Series 1: 9 laminations of 22 mm thickness in each beam
Series 2: 455 laminations of 41 mm thickness in each beam

Each beam consisted of two different grades of timber with the best grade in the outer 20 per cent of the laminations on each side. The Norwegian design specifications state that the allowable bending stresses prescribed for the structural grade which is used in the outer 20 per cent on each side of the cross section can be used even if the inner 60 per cent of the cross section consists of materials of the next lower structural grade.

The structural grading rules of NS 447 are briefly reviewed in Section 3.1. According to these rules, the timber is classified into the following groups:

- T 390
- T 100, T 210 or lower grade

T 390 represents the highest quality.

Table 1 shows the number of beams which were tested in each of the four major groups of grade combinations. The following symbols are introduced:

- A for T 390
- B for T 300
- C for T 210
- D for lower grade

Table 1 contains 42 beams. The remaining five beams had combinations of grades which fell outside the outlined pattern.

The beams are designated according to the grade combinations in such a way that the first letter indicates the grade of the outer laminations while the second letter denotes the grade of the inner laminations. The first number indicates the series to which the beam belongs. Hence, the number 1 AB 4 identifies beam number 4 of series 1 which had a combination of T 390 and T 300 materials.


Norway spruce from the district of Kirkneor in Solør was used in all beams. Kirkneor belongs to one of the best forest districts of Norway and is situated approximately 150 meters above sea level at a latitude of 61.5°.

The materials were selected at random from a sawmill in the district, and were kilndried from green condition down to a moisture content of 12 % as soon as possible after the sawing.

The materials were subsequently conditioned for several months before the production of test specimens. It appeared that the selected materials contained a rather high percentage of compression wood.

5. Fabrication.

5.1. Structural grading . . . The materials were graded after surfacing. The most important requirements of the Norwegian grading rules (NS 447) are summarized in Table 2. Additional requirements are given in NS 447 for the maximum admissible sum of knots, which is measured over a length of the piece equal to its width but not exceeding 13 cm.

Table 2 shows the grading rules of NS 447.

- Width of growth rings (mm) max 3
- Slope of grain
- Narrow face of plank max 1/3 1/10 1/7
- Wide face of plank or board middle portion max 1/4 1/6 1/3
- Width of plank or board outer portion max 1/8 1/6 1/4

* Measured in relation to the width of the percipient face of the piece under consideration.


The beams were loaded at the third-points as shown in Fig. 1. The loading arrangement, including hydraulic jacks, load cells, rollers and rocker bearings, is shown in Fig. 4. The bearing blocks were made from teak and were slightly wider than the beams.

The load was applied continuously at a rate of approximately 200 kg per minute, which is the rate of 28 kg/cm² used by Thunell (1). The deflections in the region of constant bending moment were measured by means of a dial gage with 0.01 mm accuracy, as shown in Fig. 4. The distance between the supports of the gage was 130 cm.

The center deflection was also measured in relation to the supports of the beam. This was accomplished by means of a scale fixed to the beam in its center and a string spanning between the supports.

Most of the beams of Series 1 were each provided with four electrical strain gages. Gages of the types Philips PH 9112 and Huggenberger Tropic Type K were used. The effective gage lengths were 8 and 22 mm, respectively, for the two types.

The strain gages were as a rule placed across the depth of the center cross section of the beam. The strain gages were recorded by means of a self-balancing unit of the type Brüel & Kjær. Each set of strain readings consisted of two separate readings of each gage. The strains were read in a cyclic manner and the load was recorded at the beginning as well as at the end of the cycle. Loads as well as strains were then averaged.

After the beam had been tested to failure, a portion was cut out approximately one meter from the end of the beam. From this portion clear wood properties were determined. Clear wood compressive strength was determined for the laminations in the extreme fibre of the central portion of the beam. This relatively slow rate of loading, which is only one third of the speed prescribed by the ASTM Designation D 198—27, was chosen in order to facilitate the strain readings.

The corresponding stress rate was approximately 30 kg/cm² per minute, which agrees closely with the stress rate of 28 kg/cm² used by Thunell (1).

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After the beam had been tested to failure, a portion was cut out approximately one meter from the end of the beam. From this portion clear wood properties were determined. Clear wood compressive strength was determined for the laminations in the extreme fibre of the central portion of the beam. This relatively slow rate of loading, which is only one third of the speed prescribed by the ASTM Designation D 198—27, was chosen in order to facilitate the strain readings.

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After the beam had been tested to failure, a portion was cut out approximately one meter from the end of the beam. From this portion clear wood properties were determined. Clear wood compressive strength was determined for the laminations in the extreme fibre of the central portion of the beam. This relatively slow rate of loading, which is only one third of the speed prescribed by the ASTM Designation D 198—27, was chosen in order to facilitate the strain readings.

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Two different types of failure in tension were observed. In most of the beams the wood was very much splintered in the zone of collapse, see Fig. 4. In other beams the zone of failure was very short, as shown in Fig. 5, and the character of the failure was rather brittle. The brittle failures were generally associated with relatively low strengths.

The most important test results are presented in Tables 3, 4 and 5. The load-deflection relationships were linear up to a load \( P_{\text{ult}} \) which with few exceptions ranged between 60 and 80 per cent of the ultimate load. The first wrinkles in the compression zone usually appeared at a load \( P_{\text{f}} \) somewhere between 75 and 100 per cent of the ultimate load.

The modulus of elasticity was determined from the observed deflection on that portion of the beam which had constant bending moment. Fig. 6 shows some typical relationships between observed loads and deflections. The recorded deformations included a small amount of permanent set. Beam no. 2E2 was stepwise unloaded as indicated with dotted lines in Fig. 7 in order to determine the amount of permanent set. At the second loading to a previous maximum no permanent set was recorded except at very high loads. The slopes of the dotted curves of Fig. 7 correspond to a modulus of elasticity of approximately 110 000 kg/cm², which is nine per cent higher than the modulus computed in Table 3.

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The modulus of elasticity was determined from the observed deflection on that portion of the beam which had constant bending moment. Fig. 6 shows some typical relationships between observed loads and deflections. The recorded deformations included a small amount of permanent set. Beam no. 2E2 was stepwise unloaded as indicated with dotted lines in Fig. 7 in order to determine the amount of permanent set. At the second loading to a previous maximum no permanent set was recorded except at very high loads. The slopes of the dotted curves of Fig. 7 correspond to a modulus of elasticity of approximately 110 000 kg/cm², which is nine per cent higher than the modulus computed in Table 3.
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The most important test results are presented in Tables 4, 3 and 5. The load-deflection relationships were linear up to a load (P_L) which with few exceptions ranged between 60 and 80 percent of the ultimate load. The first wrinkles in the compression zone usually appeared at a load (P_L) somewhere between 75 and 100 percent of the ultimate load.

The modulus of elasticity was determined from the observed deflection on that portion of the beam which had constant bending moment. Fig. 6 shows some typical relationships between observed loads and deflections. The recorded deformations included a small amount of permanent set. Beam no. 22e was stepwise unloaded as indicated with dotted lines in Fig. 7 in order to determine the amount of permanent set. At the second loading to a previous maximum no permanent set was recorded except at very high loads. The slopes of the dotted curves of Fig. 7 correspond to a modulus of elasticity of approximately 110,000 kg/cm², which is nine per cent higher than the modulus computed in

| Table 3.  
Test results — Series 0**<sup>)</sup> |

<table>
<thead>
<tr>
<th>Beam No.</th>
<th>h</th>
<th>j</th>
<th>P_E</th>
<th>P_W</th>
<th>P_Bk</th>
<th>P_E/P_Bk</th>
<th>P_W/P_Bk</th>
<th>E (10⁶)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0AB 1</td>
<td>6.93</td>
<td>0.21</td>
<td>0.0</td>
<td>3530</td>
<td>3720</td>
<td>3530</td>
<td>6170</td>
<td>0.81</td>
</tr>
<tr>
<td>2</td>
<td>7.05</td>
<td>0.21</td>
<td>0.0</td>
<td>3530</td>
<td>3720</td>
<td>3530</td>
<td>6170</td>
<td>0.81</td>
</tr>
<tr>
<td>3</td>
<td>7.00</td>
<td>0.21</td>
<td>0.0</td>
<td>3530</td>
<td>3720</td>
<td>3530</td>
<td>6170</td>
<td>0.81</td>
</tr>
<tr>
<td>4</td>
<td>6.92</td>
<td>0.21</td>
<td>0.0</td>
<td>3530</td>
<td>3720</td>
<td>3530</td>
<td>6170</td>
<td>0.81</td>
</tr>
<tr>
<td>6</td>
<td>7.02</td>
<td>0.21</td>
<td>0.0</td>
<td>3530</td>
<td>3720</td>
<td>3530</td>
<td>6170</td>
<td>0.81</td>
</tr>
</tbody>
</table>

| 0CD 1   | 6.99 | 0.21 | 0.0 | 3430 | 3530 | 3430 | 5920 | 0.81 | 0.81 | 465 | 532 | 140.8 |
| 2       | 7.00 | 0.21 | 0.0 | 3430 | 3530 | 3430 | 5920 | 0.81 | 0.81 | 465 | 532 | 141.8 |
| 3       | 6.94 | 0.21 | 0.0 | 3430 | 3530 | 3430 | 5920 | 0.81 | 0.81 | 465 | 532 | 141.8 |
| 4       | 6.87 | 0.21 | 0.0 | 3430 | 3530 | 3430 | 5920 | 0.81 | 0.81 | 465 | 532 | 141.7 |
| 5       | 7.06 | 0.21 | 0.0 | 3430 | 3530 | 3430 | 5920 | 0.81 | 0.81 | 465 | 532 | 141.7 |

* Failure by lateral instability.  
** Notations:  
b — width of beam.  
h — height of beam.  
j — moment of inertia.  
P_E — load at proportional limit.  
P_W — load at formation of wrinkles in the compression zone.  
P_Bk — ultimate load.  
E — modulus of elasticity.  
\(\sigma_{b,sh}—\) maximum bending stress at the first formation of wrinkles.  
\(\sigma_{sh}—\) modulus of rupture.

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** Table 4.  
Test Results — Series 1.  

<table>
<thead>
<tr>
<th>Beam No.</th>
<th>h</th>
<th>j</th>
<th>P_E</th>
<th>P_W</th>
<th>P_Bk</th>
<th>P_E/P_Bk</th>
<th>P_W/P_Bk</th>
<th>E (10⁶)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1AB 1</td>
<td>7.23</td>
<td>1.97</td>
<td>4800</td>
<td>3840</td>
<td>4600</td>
<td>4975</td>
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</tr>
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<td>3840</td>
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<td>4975</td>
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<td>0.92</td>
</tr>
<tr>
<td>3</td>
<td>7.13</td>
<td>2.07</td>
<td>4771</td>
<td>3800</td>
<td>4600</td>
<td>4975</td>
<td>0.92</td>
<td>0.92</td>
</tr>
<tr>
<td>4</td>
<td>7.13</td>
<td>1.97</td>
<td>4771</td>
<td>3800</td>
<td>4600</td>
<td>4975</td>
<td>0.92</td>
<td>0.92</td>
</tr>
<tr>
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<td>7.10</td>
<td>1.97</td>
<td>4771</td>
<td>3800</td>
<td>4600</td>
<td>4975</td>
<td>0.92</td>
<td>0.92</td>
</tr>
</tbody>
</table>

---

** Table 5.  
Test Results — Series 2.  

<table>
<thead>
<tr>
<th>Beam No.</th>
<th>h</th>
<th>j</th>
<th>P_E</th>
<th>P_W</th>
<th>P_Bk</th>
<th>P_E/P_Bk</th>
<th>P_W/P_Bk</th>
<th>E (10⁶)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2BC 1</td>
<td>7.04</td>
<td>1.85</td>
<td>4190</td>
<td>3290</td>
<td>3500</td>
<td>3500</td>
<td>0.63</td>
<td>0.63</td>
</tr>
<tr>
<td>2</td>
<td>7.03</td>
<td>1.85</td>
<td>4190</td>
<td>3290</td>
<td>3500</td>
<td>3500</td>
<td>0.63</td>
<td>0.63</td>
</tr>
<tr>
<td>3</td>
<td>7.06</td>
<td>1.85</td>
<td>4190</td>
<td>3290</td>
<td>3500</td>
<td>3500</td>
<td>0.63</td>
<td>0.63</td>
</tr>
<tr>
<td>4</td>
<td>7.06</td>
<td>1.85</td>
<td>4190</td>
<td>3290</td>
<td>3500</td>
<td>3500</td>
<td>0.63</td>
<td>0.63</td>
</tr>
<tr>
<td>5</td>
<td>6.99</td>
<td>1.85</td>
<td>4190</td>
<td>3290</td>
<td>3500</td>
<td>3500</td>
<td>0.63</td>
<td>0.63</td>
</tr>
</tbody>
</table>

** E stands for excesses.
Deflection, mm

Fig. 6. Load-deflection curves for beams 2 CD.

A summary of the observed values of the bending strength (modulus of rupture) and the modulus of elasticity is presented in Table 6, which also contains computed average values and standard deviations for the individual groups of specimens as well as the total series. Frequency distributions of the bending strength and the modulus of elasticity are presented in Figs. 8 and 9, respectively.

An analysis of variance indicated that the differences between the structural grades AB and CD are significant on the 95 per cent level of probability, while no significant difference was found between the different thicknesses of laminations.

Two beams were excluded from the statistical study, viz. beams no. 1 AB 4 and 1 AB 5. These beams need further comment. They both failed suddenly in tension, as shown in Figs. 5 and 10. In beam no. 1 AB 4, the early collapse was clearly caused by an attack of fungi. The area around the zone of failure in the outer lamination on the tension side was weakly colored in dark blue. It is doubtful whether such a discoloration would be detected during structural grading.

Beam no. 1 AB 5 apparently had more compression wood in the outer tension lamination than the other beams. The amount of compression wood was, however, not so large that it is likely that such a lamination would be excluded from the highest structural grade on the basis of the rules of NS 447. The tensile strength of the wood on each side of the zone of failure of this lamination was determined by means of small clear wood specimens. These tests did not reveal any abnormality. The low strength of the beam may possibly be ascribed to minute cracks in the fibres caused by rough handling during logging or transportation of the timber or by wind forces.

Unfortunately, the test was discontinued when the specimen broke as indicated in Fig. 10. It seems reasonable to assume that the major part of the beam was still undamaged at that time. If it is assumed that the effective cross-section of the beam was reduced by two laminations and that the strength of the other laminations corresponded to the average value for timber of grade B, it is found that the ultimate load, through a continued loading, probably could be raised from 1630 kg to 2350 kg. This would give a modulus of rupture, computed on the total cross-section, of approximately 310 kg/cm² instead of the value of 242 kg/cm² which is listed in Table 6.

A statistical study of the bending strength of all the beams of grade combinations AB and AD was conducted in the regular manner from the full line deflection curve of Fig. 7.

Table 6. Summary of Test Results.

<table>
<thead>
<tr>
<th>Series No.</th>
<th>Test No.</th>
<th>Bending strength (kg/cm²)</th>
<th>Modulus of elasticity (kg/cm² × 10⁶)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>AB</td>
<td>AD</td>
</tr>
<tr>
<td>1</td>
<td>621</td>
<td>552</td>
<td>1472.2</td>
</tr>
<tr>
<td>2</td>
<td>649**</td>
<td>537</td>
<td>151.2</td>
</tr>
<tr>
<td>3</td>
<td>609**</td>
<td>531</td>
<td>146.1</td>
</tr>
<tr>
<td>4</td>
<td>534</td>
<td>492</td>
<td>146.2</td>
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<td>5</td>
<td>512</td>
<td>592</td>
<td>136.7</td>
</tr>
<tr>
<td>6</td>
<td>568</td>
<td>132.3</td>
<td></td>
</tr>
<tr>
<td>Average</td>
<td>593</td>
<td>493</td>
<td>143.0</td>
</tr>
<tr>
<td>St. dev.</td>
<td>36</td>
<td>77</td>
<td>17.6</td>
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<tr>
<td></td>
<td></td>
<td>AB</td>
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</tr>
<tr>
<td>1</td>
<td>725</td>
<td>592</td>
<td>633</td>
</tr>
<tr>
<td>2</td>
<td>708</td>
<td>198</td>
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<td>3</td>
<td>625</td>
<td>691</td>
<td>550</td>
</tr>
<tr>
<td>4</td>
<td>472**</td>
<td>600</td>
<td>404</td>
</tr>
<tr>
<td>5</td>
<td>242**</td>
<td>631</td>
<td>195</td>
</tr>
<tr>
<td>6</td>
<td>624</td>
<td>127.8</td>
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</tr>
<tr>
<td>Average</td>
<td>621</td>
<td>622</td>
<td>566</td>
</tr>
<tr>
<td>St. dev.</td>
<td>84</td>
<td>40</td>
<td>79</td>
</tr>
</tbody>
</table>

*) Excluded from the statistical study.
** ) Failure by instability.
was, however, not so large that it is likely that such a lamination would be excluded from the highest structural grade on the basis of the rules of NS 447.

The tensile strength of the wood on each side of the zone of failure of this lamination was determined by means of small clear wood specimens. These tests did not reveal any abnormality. The low strength of the beam may possibly be ascribed to minute cracks in the fibres caused by rough handling during logging or transportation of the timber or by wind forces.

Unfortunately, the test was discontinued when the specimen broke as indicated in Fig. 10. It seems reasonable to assume that the major part of the beam was still undamaged at that time. If it is assumed that the effective cross-section of the beam was reduced by two laminations and that the strength of the other laminations corresponded to the average value for timber of grade B, it is found that the ultimate load, through a continued loading, probably could be raised from 1630 kg to 2350 kg. This would give a modulus of rupture, computed on the total cross section, of approximately 310 kg/cm² instead of the value of 242 kg/cm² which is listed in Table 6.

A statistical study of the bending strength of all the beams of grade combinations AB and AD in the regular manner from the full line deflection curve of Fig. 7.

A summary of the observed values of the bending strength (modulus of rupture) and the modulus of elasticity is presented in Table 6, which also contains computed average values and standard deviations for the individual groups of specimens as well as the total series. Frequency distributions of the bending strength and the modulus of elasticity are presented in Figs. 8 and 9, respectively.

An analysis of variance indicated that the differences between the structural grades AB and CD are significant on the 5 per cent level of probability, while no significant difference was found between the different thicknesses of laminations.

Two beams were excluded from the statistical study, viz. beams no. 1 AB 4 and 1 AB 5. These beams need further comment. They both failed suddenly in tension, as shown in Figs. 5 and 10. In beam no. 1 AB 4, the early collapse was clearly caused by an attack of fungi. The area around the zone of failure in the outer lamination on the tension side was weakly colored in dark blue. It is doubtful whether such a discolor would be detected during structural grading.

Beam no. 1 AB 5 apparently had more compression wood in the outer tension lamination than the other beams. The amount of compression wood

---

**Table 6. Summary of Test Results.**

<table>
<thead>
<tr>
<th>Series No.</th>
<th>Test No.</th>
<th>Bending strength (kg/cm²)</th>
<th>Modulus of elasticity (kg/cm²·m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>AB</td>
<td>AD</td>
</tr>
<tr>
<td>1</td>
<td>628**</td>
<td>628</td>
<td>532</td>
</tr>
<tr>
<td>2</td>
<td>648**</td>
<td>517</td>
<td>151.2</td>
</tr>
<tr>
<td>3</td>
<td>608**</td>
<td>531</td>
<td>146.5</td>
</tr>
<tr>
<td>4</td>
<td>514</td>
<td>492</td>
<td>146.2</td>
</tr>
<tr>
<td>5</td>
<td>542</td>
<td>522</td>
<td>138.3</td>
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<tr>
<td>6</td>
<td>568</td>
<td>568</td>
<td>132.3</td>
</tr>
<tr>
<td>Average</td>
<td>593</td>
<td>493</td>
<td>143.0</td>
</tr>
<tr>
<td>St. dev.</td>
<td>54</td>
<td>57</td>
<td>70</td>
</tr>
</tbody>
</table>

---

**) Excluded from the statistical study.
***) Failure by instability.
assuming 350 kg/cm² for 1 AB 5, yielded an average value of 187 kg/cm² and a standard deviation of 86 kg/cm², instead of the values presented in Table 6.

It was not considered reasonable to assume that weaknesses such as those described above tend to appear more often in the highest structural grade than in the lower ones. It therefore seems justified to exclude the two above-mentioned beams from the comparison between the different types of beams which is presented in Table 6.

The results of these two tests as well as others clearly demonstrated the importance of high strength in the outer laminations on the tension side. The theory of the mechanism of failure outlined by the author (4) also predicts that the strength of the extreme tension fibres greatly influences the strength of the member. Great care should always be taken in order to select the very best materials for use on the tension side. The author believes that existing statistical analyses of the effects of knots in laminated beams, which are based on the assumption of a linear stress distribution across the beam at failure, greatly underestimate the strength of the member.

Table 6 shows average moisture content and specific gravity of the different types of beams. The variations are very small and the beams with the highest average moisture content also had the highest average specific gravity. The results in Tables 3, 4, 5 and 6 are, therefore, directly comparable without any corrections for moisture content or specific gravity.

No failure was observed in the glue lines during the testing of the beams. Also the tests of the glue lines by means of conventional shear block specimens indicated that strong and dependable glue lines had been obtained in all the beams.

8. Comparison with Solid Beams.

A relatively large investigation of the strength properties of solid beams of Norway spruce will be executed at the Norwegian Institute of Wood Working and Wood Technology in the near future. Before the results of that investigation are available, very little information is at hand for comparative purposes.

The allowable stresses given in the Norwegian design standard for timber structures NS 446 (1) are probably to some extent based on the test results obtained by Thunell (3) in an investigation of Swedish Redwood. It may, therefore, be of interest to compare the strength properties of the laminated beams with those obtained by Thunell. Such a comparison is shown in Table 8, where the data for the solid beams have been corrected for a small difference in the moisture content between the two types of beams.

The coefficients of variance are listed in the parentheses of Table 8. It should be noted here that the variances of the two series are not directly comparable. The tests by Thunell included material from different districts of Sweden, while all the materials for the author's investigation came from a single district in Norway.

This comparison is also problematic since the investigation by Thunell included beams of different heights. His tests clearly indicated increasing strength with decreasing height. Since the laminated beams were higher than the majority of the solid beams, Table 8 tends to underestimate the relative strength of the laminated beams.

Table 8 indicates that the modulus of rupture as well as the modulus of elasticity of the laminated beams made from Norway spruce are on the average approximately 25 per cent higher than the corresponding values for solid timber beams of Swedish Redwood. The coefficients of variance seem to be lowest for the laminated beams.

9. Comparison with NS 446.

In order to compare the test results with the Norwegian design specifications (NS 446) it will be necessary to make some assumptions with respect to factors of safety, effects of sustained load etc. The allowable bending stresses for sustained load will be computed from the following formula

$$\sigma = \frac{1}{n_s} \cdot n_n \cdot (\sigma_a - 2\sigma_i)$$

where

$\sigma_a$ = the observed average modulus of rupture

$\sigma_i$ = the observed standard deviation

$n_n$ = factor of safety

$n_s$ = height factor

$n_i$ = sustained load factor.

The values of $\sigma_a$ and $\sigma_i$ have been determined by means of the tests and are listed in Table 6. In a normal distribution only 2.5 per cent of the total number of tests results will fall below the value $(\sigma_a - 2\sigma_i)$.

Table 8.

<table>
<thead>
<tr>
<th>Series</th>
<th>AB</th>
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<th>DC</th>
<th>CD</th>
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<td>11.2</td>
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<tr>
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<td>12.0</td>
<td>12.0</td>
<td>11.9</td>
<td>12.0</td>
</tr>
<tr>
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<td>11.6</td>
<td>13.6</td>
<td>13.2</td>
<td>13.4</td>
<td></td>
</tr>
<tr>
<td>ALL</td>
<td>11.6</td>
<td>12.0</td>
<td>12.8</td>
<td>12.2</td>
<td>12.2</td>
</tr>
</tbody>
</table>

*) From reference (3). Corrected to 12.2 per cent moisture content.

In parentheses: Coefficients of variance.
Table 7 shows average moisture content and specific gravity of the different types of beams. The variations are very small and the beams with the highest average moisture content also had the highest average specific gravity. The results in Tables 3, 4, 5 and 6 are, therefore, directly comparable without any corrections for moisture content or specific gravity.

No failure was observed in the glue lines during the testing of the beams. Also the tests of the glue lines by means of conventional shear block specimens indicated that strong and dependable glue lines had been obtained in all the beams.

8. Comparison with Solid Beams.

A relatively large investigation of the strength properties of solid beams of Norway spruce will be executed at the Norwegian Institute of Wood Working and Wood Technology in the near future. Before the results of that investigation are available, very little information is at hand for comparative purposes.

The allowable stresses given in the Norwegian design standard for timber structures NS 446 (1) are probably to some extent based on the test results obtained by Thunell (2) in an investigation of Swedish Redwood. It may, therefore, be of interest to compare the strength properties of the laminated beams with those obtained by Thunell. Such a comparison is shown in Table 8, where the data for the solid beams have been corrected for a small difference in the moisture content between the two types of beams.

The coefficients of variance are listed in the parentheses of Table 8. It should be noted here that the variances of the two series are not directly comparable. The tests by Thunell included materials from different districts of Sweden, while all the materials for the author’s investigation came from a single district in Norway.

This comparison is also problematic since the investigation by Thunell included beams of different heights. His tests clearly indicated increasing strength with decreasing height. Since the laminated beams were higher than the majority of the solid beams, Table 8 tends to underestimate the relative strength of the laminated beams.

Table 8 indicates that the modulus of rupture as well as the modulus of elasticity of the laminated beams made from Norway spruce are on the average approximately 25 per cent higher than the corresponding values for solid timber beams of Swedish Redwood. The coefficients of variance seem to be lowest for the laminated beams.

9. Comparison with NS 446.

In order to compare the test results with the Norwegian design specifications (NS 446) it will be necessary to make some assumptions with respect to factors of safety, effects of sustained load etc. The allowable bending stresses for sustained load will be computed from the following formula:

\[ \sigma_a = \frac{1}{n_s} \cdot \frac{S_a - 2S_s}{n_h} \]

where

- \( \sigma_a \) = the observed average modulus of rupture
- \( S_a \) = the observed standard deviation
- \( n_s \) = factor of safety
- \( n_h \) = sustained load factor.

The values of \( \sigma_a \) and \( n_s \) have been determined by means of the tests and are listed in Table 6.

Table 8 indicates that the total number of test results will fall below the value (\( \sigma_a - 2S_s \)).

![Fig. 10. Failure in beam no. 1 AB.](image)

![Fig. 11. Failures through edge knots.](image)
A factor of safety of 1.5 will be used. Several empirical formulas exist which account for the decrease in strength of wood beams with increasing height. In laminated beams, which may differ very much in height from case to case, this effect should preferably be considered separately in each case. However, since NS 446 does not specify an allowable strength that varies with the height of the beam it seems advisable to base the allowable stresses on a fairly large beam height.

Wood Handbook (6) gives the following empirical formula for the height factor

\[ n_H = 0.81 \left( \frac{H^2 + 44}{H^2 + 88} \right) \]

where \( H \) is the height of the beam, measured in inches.

It seems reasonable to base the allowable stresses for laminated beams on an average height of 75 cm (10") since the experimental investigation included beams of approximately 20 cm (8") height, a reduction factor

\[ n_H = \frac{n_m}{n_H} = 0.86 / 1.10 = 0.8 \]

should be introduced to account for the reduced strength of higher beams.

The ratio of the sustained load strength to the strength as found in tests of approximately half an hour duration may according to Wood (1) be estimated to 0.60.

**Table 9. Comparison of Test Results with NS 446.**

**A) Bending Stress (kg/cm²).**

<table>
<thead>
<tr>
<th>Structural grade</th>
<th>NS 446</th>
<th>Laminated beams</th>
<th>Allowable stress</th>
<th>Suggested</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Eₕ</td>
<td>σₕ</td>
<td>σₕ/σₕ</td>
<td>Average modulus of elasticity</td>
</tr>
<tr>
<td>T390</td>
<td>130</td>
<td>156</td>
<td>1.20</td>
<td>604</td>
</tr>
<tr>
<td>T300</td>
<td>100</td>
<td>130</td>
<td>1.30</td>
<td>148</td>
</tr>
<tr>
<td>T210</td>
<td>70</td>
<td>98</td>
<td>1.40</td>
<td>123</td>
</tr>
</tbody>
</table>

**B) Modulus of Elasticity (kg/cm²).**

<table>
<thead>
<tr>
<th>Structural grade</th>
<th>NS 446</th>
<th>Laminated beams</th>
<th>Allowable stress</th>
<th>Suggested</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Eₕ</td>
<td>Eₕ</td>
<td>Eₕ/Eₕ</td>
<td>Average modulus of elasticity</td>
</tr>
<tr>
<td>T390</td>
<td>100 000</td>
<td>100 000</td>
<td>1.0</td>
<td>146 000</td>
</tr>
<tr>
<td>T300</td>
<td>90 000</td>
<td>90 000</td>
<td>1.0</td>
<td>134 000</td>
</tr>
<tr>
<td>T210</td>
<td>70 000</td>
<td>70 000</td>
<td>1.0</td>
<td>130 000</td>
</tr>
</tbody>
</table>

1) A significant difference in strength and stiffness was observed between the beams of the highest and the lowest grade.

2) No significant difference was found for the different thicknesses of laminations. Beams with laminations of 2" thickness had, however, slightly lower average strength and stiffness than beams with thinner laminations.

3) The strength of laminated beams depends very much on the quality of the outer laminations on the tension side. Even very weak traces of fungi may reduce the strength of the beam considerably. Care should also be taken in order to avoid compression wood in these laminations.

4) The allowable stresses specified in NS 446 are quite reasonable. A minor increase in the allowable bending stress for laminated timber of the weakest grade seems justified.

5) The moduli of elasticity given in the standard specifications are too conservative. An increase of 20,000 kg/cm² for laminated beams seems justified for all the structural grades.

6) Additional tests should be carried out in order to substantiate the validity of the two preceding conclusions for materials from other districts.

**11. REFERENCES**

A factor of safety of 1.5 will be used. Several empirical formulas exist which account for the decrease in strength of wood beams with increasing height. In laminated beams, which may differ very much in height from case to case, this effect should preferably be considered separately in each case. However, since NS 446 does not specify an allowable stress that varies with the height of the beam it seems advisable to base the allowable stresses on a fairly large beam height.

Wood Handbook (6) gives the following empirical formula for the height factor

$$n_h = 0.81 \cdot (H^2 + 143) / (H^2 + 88)$$

where $H$ is the height of the beam, measured in inches. It seems reasonable to base the allowable stresses for laminated beams on an average height of 75 cm ($10^2$). Since the experimental investigation included beams of approximately 20 cm ($8^2$) height, a reduction factor

$$n_h = n_{0.81} / n_h = 0.86 / 1.10 = 0.8$$

should be introduced to account for the reduced strength of higher beams.

The ratio of the sustained load strength to the strength as found in tests of approximately half an hour duration may according to Wood (1) be estimated to 0.60.

**Table 9.** Comparison of Test Results with NS 446.

### A) Bending Stress (kg/cm²).

<table>
<thead>
<tr>
<th>Structural grade</th>
<th>Solid timber $\sigma_{NS}$</th>
<th>Laminated timber $\sigma_{NS}$</th>
<th>Ratio $n_{NS}$</th>
<th>Average modulus of rupture $\sigma_m$</th>
<th>Standard deviation $\sigma_m$</th>
<th>Computed allowable stress $\sigma_a$</th>
<th>Allowable stress $\sigma_e$</th>
<th>Ratio $\sigma_e / \sigma_m$</th>
</tr>
</thead>
<tbody>
<tr>
<td>T190</td>
<td>130</td>
<td>156</td>
<td>1.20</td>
<td>604</td>
<td>57</td>
<td>117</td>
<td>116</td>
<td>1.20</td>
</tr>
<tr>
<td>T200</td>
<td>100</td>
<td>130</td>
<td>1.30</td>
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<td>71</td>
<td>130</td>
<td>130</td>
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<tr>
<td>T210</td>
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<td>98</td>
<td>1.40</td>
<td>123</td>
<td>58</td>
<td>110</td>
<td>107</td>
<td>1.30</td>
</tr>
</tbody>
</table>

### B) Modulus of Elasticity (kg/cm²).

<table>
<thead>
<tr>
<th>Structural grade</th>
<th>Solid timber $E_{NS}$</th>
<th>Laminated timber $E_{NS}$</th>
<th>Ratio $n_{NS}$</th>
<th>Average modulus of elasticity $E_m$</th>
<th>Standard deviation $E_m$</th>
<th>Computed design M.E. $E_a$</th>
<th>Design M.E. $E_b$</th>
<th>Ratio $E_b / E_m$</th>
</tr>
</thead>
<tbody>
<tr>
<td>T190</td>
<td>100 000</td>
<td>100 000</td>
<td>1.0</td>
<td>164 000</td>
<td>18 000</td>
<td>126 000</td>
<td>120 000</td>
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</tr>
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<td>100 000</td>
<td>90 000</td>
<td>1.22</td>
</tr>
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</table>

1) A significant difference in strength and stiffness was observed between the beams of the highest and the lowest grade.

2) No significant difference was found for the different thicknesses of laminations. Beams with laminations of 2" thickness had, however, slightly lower average strength and stiffness than beams with thinner laminations.

3) The strength of laminated beams depends very much on the quality of the outer laminations on the tension side. Even very weak traces of fungi may reduce the strength of the beam considerably. Care should also be taken in order to avoid compression wood in these laminations.

4) The allowable stresses specified in NS 446 are quite reasonable. A minor increase in the allowable bending stress for laminated timber of the weakest grade seems justified.

5) The modulus of elasticity given in the standard specifications are too conservative. An increase of 30 000 kg/cm² for laminated beams seems justified for all the structural grades.

### REFERENCES