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# The strength of glued laminated timber (GLULAM) - Influence of lamination qualities and strength of finger joints -

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## 1 Preface

In annex 2 of the draft of EUROCODE 5 "Common unified rules for timber structures" published by the Commission of the European Communities in October 1987 to seek comments by the member states a proposal for requirements of laminations and end-jointing for glued laminated timber grades is given with appertaining characteristic strength values for these grades. It is the intention of this paper to explain the background ideas which led to this proposal and to challenge any comments on this glulam strength system. This glulam grade system is mainly based on the bending strength whereas other strength properties, i.e. tensile and compressive strength perpendicular to grain as well as shear strength values, are estimated data based on experience at the present time.

## 2 Bending strength

### 2.1 Volume effect

The size effect of the stressed volume on the strength of timber is usually called the volume effect. In Karlsruhe |1| the bending strength of 42 glulam beams in structural sizes was tested in the course of a research project on glulam beams made of European whitewood (picea abies). One aim in this project was to study the volume effect. Using a constant beam width of 100 mm, the depth and the length of the beams was varied in two main test series:

Series no. I: Constant depth of 300 mm and different load distance from 0 to 3500 mm of a four-point test beam;

Series no. II: Constant load distance of 2000 mm and different beam depth from 167 to 1250 mm.

For all test beams the location and size of the knots, the density, and the modulus of elasticity (MOE) of the outer two laminations on the tension side was checked before manufacturing the glulam beams. The MOE was tested dynamically (see |2|).

From three replications of each test beam one was made with an outer lamination satisfying the quality requirements of the German grading class I (DIN 4074), whereas all other beams were made from grading class II laminations. In order to avoid any beam failure due to finger joints, there were no finger joints in the outer two laminations on the tension side between the loading points, that is in the high-stressed zone. Only in two comparative test series there were finger joints intentionally placed between the two loading points.

All beam dimensions and loading schemes are listed in table 1 and 2 together with the test results. These results are also plotted in fig. 1 and 2.

From fig. 1 can be realized that the bending strength due to wood failure clearly decreases with increasing distance $\Delta$ of the loading points. With finger joints in the high-stressed zone, however, the probability of failure caused by finger joints increases (see test series no. I.4 and I.5, where 5 beams from 6 failed in the finger joints). For glulam beams of practical dimensions can be concluded from these results that the effect of the beam length is determined by the frequency of occurrence of finger joints in the high-stressed zone of the glulam beam.

From fig. 2 can be realized that the bending strength of glulam beams decreases with increasing beam depth up to 500 mm. For beams deeper than 500 mm, however, it may be concluded that there is no further considerable decrease of the glulam beam's bending strength. For beams failing in a finger joint there was no relationship between bending strength and beam depth. From table 3 with all beams which failed in a finger joint can be stated that the bending strength of beams with 330 mm depth was on the same strength level as with beams of 1000 mm dept.

The problem of volume effect in glulam beams is obviously reduced to the problem of the occurrence frequency of finger joints in the high-stressed tensile zones of the beams. The occurrence of finger joints in a glulam beam depends, however, mainly on the grading technique in the glulam factories, e.g. how often a board is cut to pick out zones of lower grade and end-jointed again.

A general rule to consider the volume effect can not be presented for the time being.

## 2.2 Requirements for finger joints

The bending tests conducted with glulam beams of 330 mm depth exhibited that the bending strength depends to a high degree on the tensile strength of the finger joints. For this reason the tensile strength of altogether 21 test specimens of those finger joints were tested, that were produced on the same day as the glulam beams. The mean tensile strength of these finger joints was 32.7 $N/mm^2$ with a standard deviation of 6.8 $N/mm^2$. It is essential to point out that these tests were not performed according to ISO 8375, but with a test set-up which excluded any lateral displacement of the 150 mm test length. Lateral displacements of laminations in a glulam beam under tensile stresses are prevented as well, whereas in the ISO 8375 test procedure for determining the tensile strength of boards in structural sizes a lateral displacement will occurr due to the inhomogenity of the timber and thus will reduce the calculated value of the tensile strength. For this reason the tensile strength of the laminations tested in the course of this project can directly be assumed to be the tensile strength of the finger joints in the glulam beams. This is verified by the bending strengths of those beams which failed in the finger joints of the outer tension laminations, see table 3. It can also be realized by this effect that in the zone of finger joints it cannot be anticipated to increase the load-carrying capacity of glulam beams in consequence of the so-called lamination effect.

These test results were confirmed by numerous simulation calculations using the "Karlsruhe calculation model" |1; 3; 4|. As a result it can be assumed that as a good approach the bending strength of glulam beams with failure in the finger joints is equal to the tensile strength of the corresponding finger joints:

$$f_{m;glulam} \sim f_{t,o;fj} \qquad (1)$$

A current quality control of the tensile strength of the finger joints is difficult to realize. The bending strength of finger joints, $f_{m;fj}$, is, however, in many countries under permanent quality control according to a stipulated test method. A harmonized test method is under preparation as a CEN-standard.

The ratio of tensile strength to bending strength of finger joints can be assumed to |5; 6|:

$$\frac{f_{t,o;fj}}{f_{m;fj}} \sim 0.8 \qquad (2)$$

More information by tests aimed at this relationship is under performance. From eq. (1) and eq. (2) follows:

$$f_{m;glulam} \sim 0.8 \cdot f_{m;fj} \tag{3}$$

The characteristic strength values for timber are defined in the draft EUROCODE 5 as the population 5-percentile values. Assuming a coefficient of variation of the bending strength of glulam beams as well as of the bending strength of the finger joints in the same order (e.g. 10 - 15 %) and the same type of the distribution function for both properties, it can be said

$$f_{m,k;glulam} \sim 0.8 \cdot f_{m,k;fj} \tag{4}$$

Hence, the characteristic bending strength of the finger joints in the high-stressed zone of a glulam beam must be approximately 25 % higher than the characteristic bending strength of a defined glulam strength class. This requirement is inserted in table A 2.5 in annex 2 of the draft EUROCODE 5.

## 2.3 Requirements for laminations

For all beams with a depth of at least 250 mm and a distance of the loading points of at least 2000 mm that is for all beams with a relatively big high-stressed volume, and with wood failure, the bending strength values are listed in table 4. The mean bending strength figures up to 33.7 N/mm², with a standard deviation of 3.5 N/mm².

Using the computer model, the mean bending strength for all beams with wood failure came up to 34.4 N/mm², with the same standard deviation of 3.5 N/mm² (the simulated beams having a depth of 600 mm were of comparable grading class as the test beams). The mean tensile strength of the laminations, simulated in this computer calculation, was 33.8 N/mm², with a standard deviation of 8.5 N/mm². In this simulation each board was subdivided into elements of 150 mm length, with each element being assigned to a calculated tensile strength on the basis of a regression equation (see |3|). The board tensile strength was equalized to the lowest "element tensile strength" of the board.

The tests for finding the regression equation mentioned above were performed with a test set-up which prevented any lateral deformation of the test specimens. Thus, the tensile strength of a simulated board is higher than the tensile strength of boards which are tested in accordance to ISO 8375.

Assuming that the increase of strength due to prevented lateral deformation comes up to approximately 40 % (see |5| and |7|), it can be recalculated from the simulated board tensile strength values, that the tensile strength tested in accordance to ISO 8375 must be approximately 24 N/mm², with a standard deviation of 6 N/mm².

A comparison of tested and simulated strength values is listed in table 5 showing that it is possible to produce glulam beams with a characteristic bending strength distinctly higher than the characteristic tensile strength (investigated in line with ISO 8375 !) of the single boards of the beam. This result found favour when table A 2.5 in the draft EUROCODE 5 was proposed.

## 3 Other strength properties

In case of tension parallel to grain high stresses are distributed across the total cross-section. Therefore, the tensile strength is dependent on the strength properties of all laminations, and to a certain degree the weakest laminations control the strength. By gluing together all laminations, the strength of the total cross-section increases, however, considerably because of the redistribution of forces corresponding to the individual elasticity of the laminations. Due to this effect the variation of the strength decreases. Hence, the characteristic tensile strength of a glulam cross-section is higher than that of the weakest individual lamination.

In curved and cambered glulam beams the highest tensile stresses perpendicular to grain occur generally in the zone of the inner laminations. A melioration effect by gluing together different laminations does not exist. Hence, the characteristic tensile strength perpendicular to grain is in accordance with that of the individual inner laminations.

In case of compression parallel to grain the gluing effect is similar to that under tensile stresses. Therefore, an increased characteristic compressive strength of glulam members is ascertained in comparison to the individual laminations.

In case of compression perpendicular to grain the outer laminations, where the loads are directly imposed, control the characteristic strength, with no substantial variation-reducing effect.

The same effect as for tension perpendicular to grain applies when shear stresses are induced by shear forces (in bending members).

The modulus of elasticity is correlated to several physical properties of the wood (such as density and knot area ratio). Hence, the mean value of the modulus of elasticity increases when individual laminations of different physical properties are composed by adhesives. The characteristic modulus of elasticity is approximately 80 % of the mean value, based on the assumption of a coefficient of variation of 12 %.

## 4 References

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|2| Görlacher, R. 1984: Ein neues Meßverfahren zur Bestimmung des Elastizitätsmoduls von Holz. Holz Roh-Werkstoff 42: S. 219 - 222.

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|4| Colling, F. 1988: Estimation of the effect of different grading criterions on the bending strength of glulam beams using the "Karlsruhe calculation model". IUFRO-Meeting, Turku, Finland

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|6| Johansson, C.-J. 1988: High-strength laminations for glulam. IUFRO-Meeting, Turku, Finland.

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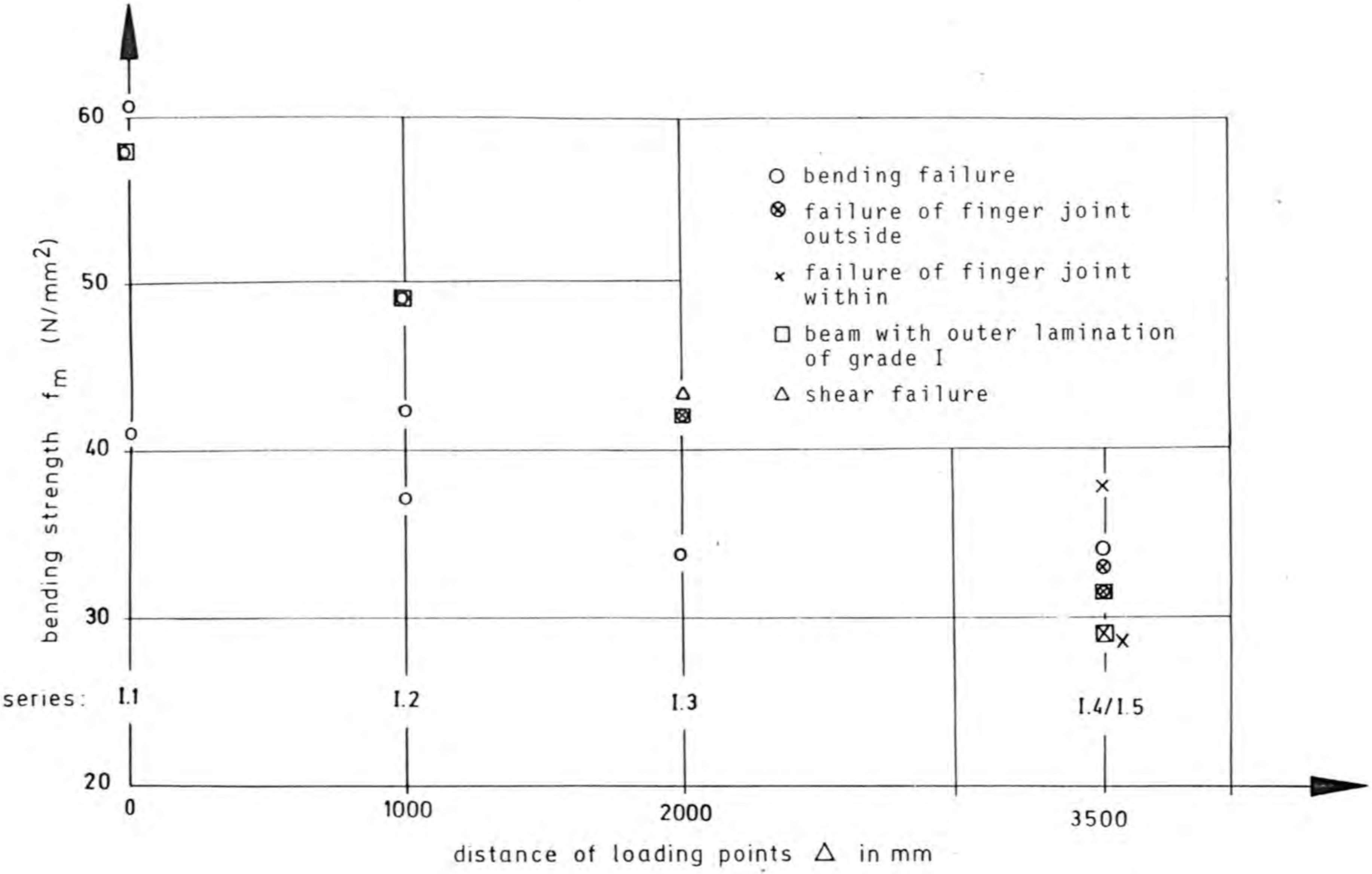



Fig. 1: Bending strength $f_m$ over distance of loading points △ ;
beam depth H = 330 mm

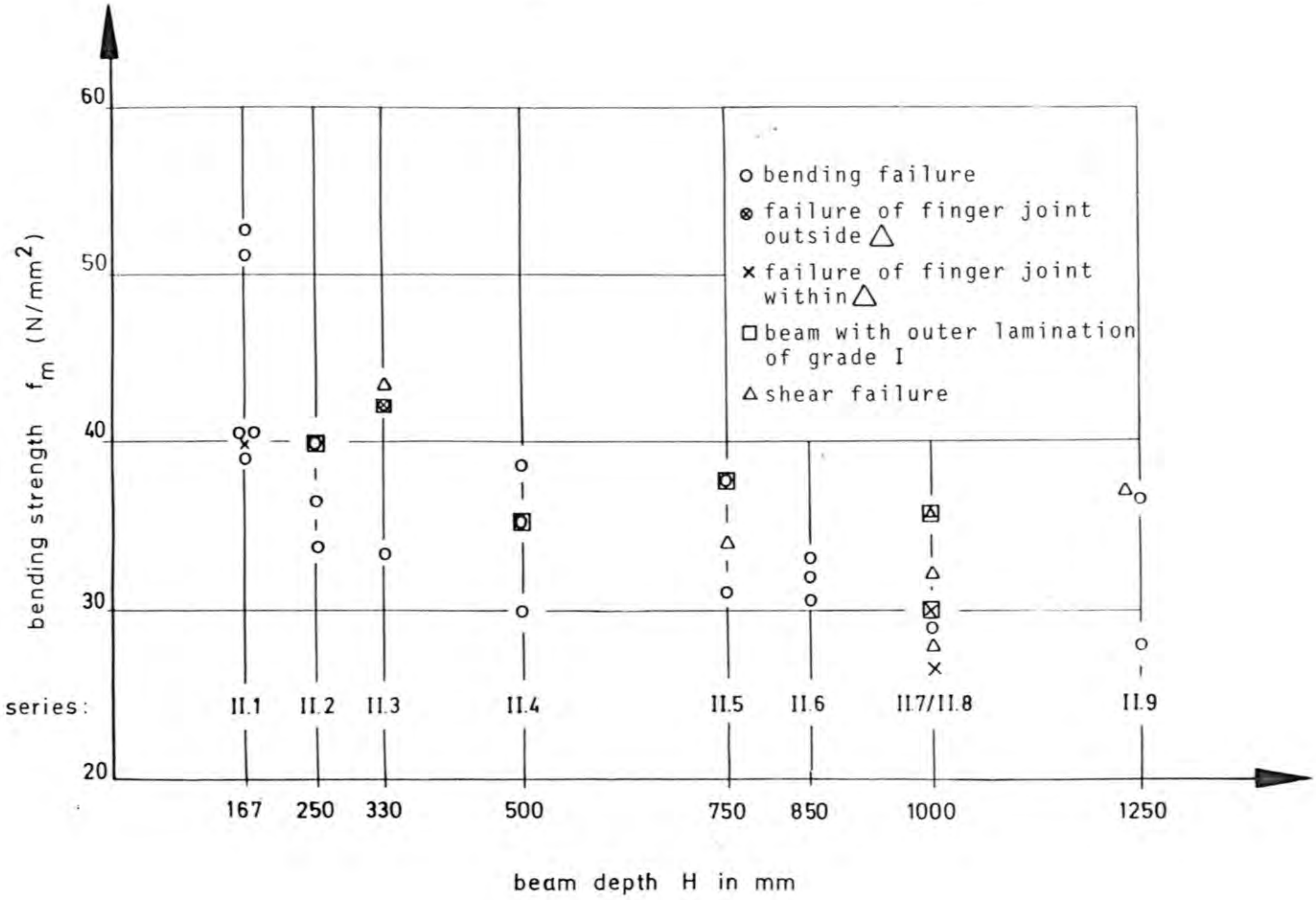
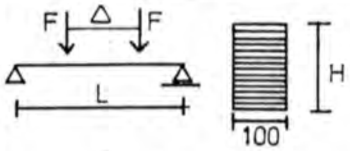



Fig. 2 : Bending strength $f_m$ over beam depth H (distance of loading points △ = 2000 mm)

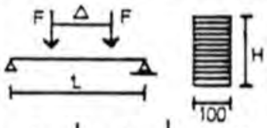
Table 1: Dimensions of test beams, test set-up and test results of series no. I




| Test No. | L mm | Δ mm | H mm | Modulus of elasticity E $N/mm^2$ | bending strength single $f_m$ $N/mm^2$ | bending strength mean $f_m$ $N/mm^2$ | failure mode |
|---|---|---|---|---|---|---|---|
| I.1-1 | | | | 10 420 | 57,1 | | Knot |
| I.1-2 | 3750 | 0 | 330 | 11 990 | 60,8 | 52,9 | Knot |
| I.1-3 | | | | 9 760 | 40,9 | | Knot |
| I.2-1 | | | | 11 880 | 49,2 | | Knot |
| I.2-2 | 3750 | 1000 | 330 | 10 500 | 42,5 | 43,0 | Knot |
| I.2-3 | | | | 9 800 | 37,2 | | Knot |
| I.3-1 | | | | 12 280 | 42,4 | | f.j.[1]) outside Δ: $f_m$ = 26,1 $N/mm^2$ |
| I.3-2 | 4650 | 2000 | 330 | 12 460 | 43,1 | 39,6 | shear failure at $f_v$ = 2,7 $N/mm^2$ |
| I.3-3 | | | | 11 270 | 33,4 | | Knot |
| I.4-1 | | | | 12 460 | 31,7 | | f.j.[1]) outside Δ: $f_m$ = 27,8 $N/mm^2$ |
| I.4-2 | 6900 | 3500 | 330 | 11 820 | 34,2 | 33,1 | Knot |
| I.4-3 | | | | 12 730 | 33,3 | | f.j.[1]) outside Δ: $f_m$ = 28,4 $N/mm^2$ |
| I.5-1 | | | | 13 350 | 29,2 | | f.j.[1]) |
| I.5-2 | 6900 | 3500 | 330 | 11 450 | 37,9 | 32,1 | f.j.[1]) |
| I.5-3 | | | | 10 220 | 29,1 | | f.j.[1]) |

[1]) f.j. = finger joint

Table 2: Dimensions of test beams, test set-up and test results of series no. II




| Test No. | L mm | Δ mm | H mm | Modulus of elasticity E $N/mm^2$ | bending strength single $f_m$ $N/mm^2$ | bending strength mean $f_m$ $N/mm^2$ | failure mode |
|---|---|---|---|---|---|---|---|
| II.1-1 | | | | - | 38,9 | | Knot |
| II.1-2 | | | | - | 40,3 | | Knot |
| II.1-3 | | | | - | 40,3 | | Knot |
| | 3700 | 2000 | 167 | | | 43,9 | |
| II.1-4 | | | | - | 51,1 | | Knot |
| II.1-5 | | | | - | 52,6 | | Knot |
| II.1-6 | | | | - | 39,9 | | f.j.1) |
| II.2-1 | | | | 12 660 | 39,9 | | Knot |
| II.2-2 | 3300 | 2000 | 250 | 12 280 | 33,6 | 36,6 | Knot |
| II.2-3 | | | | 11 590 | 36,4 | | Knot |
| II.3-1 | | | | 12 280 | 42,4 | | f.j.1) outside Δ: $f_m$ = 26,1 $N/mm^2$ |
| II.3-2 | 4650 | 2000 | 330 | 12 460 | 43,1 | 39,6 | shear failure at $f_v$ = 2,7 $N/mm^2$ |
| II.3-3 | | | | 11 270 | 33,4 | | Knot |
| II.4-1 | | | | 10 960 | 35,3 | | Knot |
| II.4-2 | 4650 | 2000 | 500 | 10 430 | 38,5 | 34,6 | Knot |
| II.4-3 | | | | 10 610 | 29,9 | | Knot |
| II.5-1 | | | | 10 730 | 37,7 | | Knot |
| II.5-2 | 6000 | 2000 | 750 | 10 220 | 34,1 | 34,2 | shear failure at $f_v$ = 3,2 $N/mm^2$ |
| II.5-3 | | | | 9 730 | 31,1 | | Knot |
| II.6-1 | | | | 9 750 | 30,5 | | Knot |
| II.6-2 | 9000 | 2000 | 850 | 10 140 | 32,0 | 31,8 | Knot |
| II.6-3 | | | | 10 750 | 33,0 | | Knot |
| II.7-1 | | | | 9 640 | 35,6 | | shear failure at $f_v$ = 3,2 $N/mm^2$ |
| II.7-2 | 7500 | 2000 | 1000 | 9 940 | 28,1 | 30,9 | shear failure at $f_v$ = 2,6 $N/mm^2$ |
| II.7-3 | | | | 8 680 | 28,9 | | Knot |
| II.8-1 | | | | 10 780 | 30,0 | | f.j.1) |
| II.8-2 | 7500 | 2000 | 1000 | 10 680 | 31,9 | 29,6 | shear failure at $f_v$ = 2,9 $N/mm^2$ |
| II.8-3 | | | | 9 730 | 26,9 | | f.j.1) |
| II.9-1 | | | | 9 950 | 36,6 | | Knot |
| II.9-2 | 11800 | 2000 | 1250 | 9 720 | 27,9 | 33,8 | Knot |
| II.9-3 | | | | 10 030 | 36,8 | | shear failure at $f_v$ = 2,3 $N/mm^2$ |

Table 3: Bending strength $f_m$ from test beam with failures in the finger joints

| Test no. | beam depth H mm | bending strength $f_m$ [1) ] $N/mm^2$ |
|---|---|---|
| I.3-1 resp. II.3-1 | 330 | 26,1 |
| I.4-1 | 330 | 27,8 |
| I.4-3 | 330 | 28,4 |
| I.5-1 | 330 | 29,2 |
| I.5-2 | 330 | 37,9 |
| I.5-3 | 330 | 29,1 |
| II.1-6 | 167 | 39,9 |
| II.8-1 | 1000 | 30,0 |
| II.8-3 | 1000 | 26,9 |
| mean | | 30,6 $N/mm^2$ |
| standard deviation | | 4,9 $N/mm^2$ |
| coefficient of variation | | 16 % |

1) strength $f_m$ calculated at the failure point (i.e. the point where the finger joint was placed)

Table 4: Bending strength values from tests with wood failure in the outer tension lamination

| Test no. | beam depth H mm | bending strength $f_m$ $N/mm^2$ |
|---|---|---|
| I.3-3 resp. II.3-3 | 330 | 33,4 |
| I.4-2 | 330 | 34,2 |
| II.2-1 | 250 | 39,9 |
| II.2-2 | 250 | 33,6 |
| II.2-3 | 250 | 36,4 |
| II.4-1 | 500 | 35,3 |
| II.4-2 | 500 | 38,5 |
| II.4-3 | 500 | 29,9 |
| II.5-1 | 750 | 37,7 |
| II.5-3 | 750 | 31,1 |
| II.6-1 | 850 | 30,5 |
| II.6-2 | 850 | 32,0 |
| II.6-3 | 850 | 33,0 |
| II.7-3 | 1000 | 28,9 |
| II.9-1 | 1250 | 36,6 |
| II.9-2 | 1250 | 27,9 |
| mean | | 33,7 $N/mm^2$ |
| standard deviation | | 3,5 $N/mm^2$ |
| coefficient of variation | | 10 % |

Table 5: Comparison of tested and simulated strength values

| | mean | standard deviation | 5-percentile |
|---|---|---|---|
| $f_{m,test}^{glulam}$ | 33,7 | 3,5 | 27,8 |
| $f_{m,sim}^{glulam}$ | 34,4 | 3,5 | 28,5 |
| $f_{t,0,sim}^{lamination}$ | 33,8 | 8,5 | 19,4 |
| $f_{t,0,ISO}^{lamination}$ | 24,0 | 6,0 | 13,8 |