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# STRENGTH OF GLUED LAMINATED TIMBER

by

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# STRENGTH OF GLUED LAMINATED TIMBER

## 1 Introduction

Strength and stiffness values of glued laminated timber are dependent of the design of glulam beams, i.e. the properties of the outer and inner laminations as well as the quality of the finger joints. On principle, the outer laminations are of better or at least the same quality as the inner laminations. The extreme sixth of the depth or at least two laminations on either side of the beam are defined as outer laminations. It is necessary to differentiate in that way because the outer laminations decide essentially the bending strength of the glulam beam, whereas the tension perpendicular to grain and the shear strengths are in most cases controlled by the properties of the inner laminations.

## 2 Bending strength

The bending strength of glulam beams depends especially on the tensile strength of the outer laminations. The tensile strength of a lamination is defined and tested according to ISO Standard 8375, clause 3.1.1. The strength of a lamination in a glulam beam differs, however, in two ways from that in a regular ISO 8375 tension test (strength increasing effects):

a) Lateral displacements of the laminations, occuring in a regular tension test, are prevented when the laminations are part of a glulam beam; this effect can be taken into account by a modification factor $k_1$.

b) Longitudinal strains of a weak zone of the lamination (i.e. zones with knots and low modulus of elasticity) are hindered by the adjacent laminations; let this be taken into account by a modification factor $k_2$.

Due to these effects it is explicable that outer laminations of a rather low characteristic tensile strength produce glulam beams of a rather high bending strength. In case of finger joints with a modulus of elasticity in the range of that of clear wood the second strength increasing effect does not exist.

Thus, the bending strength of a glulam beam can be derived by the following two basic equations:

$$\boxed{f_{m,Glulam} = k_1 \cdot k_2 \cdot f_{t,o}} \qquad (1)$$

$$\boxed{f_{m,Glulam} = k_{1,fj} \cdot f_{t,o,fj}} \qquad (2)$$

where

| | |
|---|---|
| $f_{m,Glulam}$ | mean bending strength of a glulam beam |
| $f_{t,o}$ | mean tensile strength of a lamination parallel to grain |
| $f_{t,o,fj}$ | mean tensile strength of a finger joint |

The characteristic strength is defined as a fractile, normally the 5-percentile, and can be written as

$$f_k = f\,(1 - k \cdot v) \qquad (3)$$

where

| | |
|---|---|
| $f_k$ | characteristic strength |
| $f$ | mean strength |
| $v$ | coefficient of variation |
| $k$ | constant of a statistical distribution for calculating the 5-percentile. |

k may roughly be assumed to be 1.7 or in accordance with the Gauß-distribution, $k = 1.645$.

From equ. (3) follows:

$$f_{m,k,Glulam} = k_1 \cdot k_2 \cdot f_{t,o,k} \cdot \frac{1-k\cdot v_{m,Glulam}}{1-k\cdot v_{t,o}} \quad (4)$$

and

$$f_{m,k,Glulam} = k_{1,fj} \cdot f_{t,o,k,fj} \cdot \frac{1-k\cdot v_{m,Glulam}}{1-k\cdot v_{t,o,fj}} \quad (5)$$

With

$$k_{v,1} = \frac{1-k\cdot v_{m,Glulam}}{1-k\cdot v_{t,o}}$$

and

$$k_{v,2} = \frac{1-k\cdot v_{m,Glulam}}{1-k\cdot v_{t,o,fj}} \quad (6a,\ b)$$

equs. (4 and 5) read

$$\boxed{f_{m,k,Glulam} = k_1 \cdot k_2 \cdot k_{v,1} \cdot f_{t,o,k}} \quad (7)$$

$$\boxed{f_{m,k,Glulam} = k_{1,fj} \cdot k_{v,2} \cdot f_{t,o,k,fj}} \quad (8)$$

The factors $k_{v,1}$ and $k_{v,2}$ depend on the variability of the test data and will be discussed later.

A current quality control of the tensile strength of the finger joints, $f_{t,o,fj}$ is difficult to perform in glulam factories. The bending strength of the finger joints, $f_{m,fj}$, is, however, in many countries under permanent quality control according to a stipulated test method. If the relationship between the tensile strength and the bending strength of the finger joint is sufficiently known, i.e.

$$f_{t,o,fj} = k_3 \cdot f_{m,fj} \tag{9}$$

and

$$f_{t,o,k,fj} = k_3 \cdot f_{m,k,fj} \cdot \frac{1-k \cdot v_{t,o,fj}}{1-k \cdot v_{m,fj}} \tag{10}$$

then equ. (8) can be replaced by

$$\boxed{f_{m,k,Glulam} = k_{1,fj} \cdot k_3 \cdot k_{v,2} \cdot k_{v,3} \cdot f_{m,k,fj}} \tag{11}$$

with

$$k_{v,3} = \frac{1-k \cdot v_{t,o,fj}}{1-k \cdot v_{m,fj}} \tag{12}$$

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LARSEN |1| performed tests to find the relationship between the tensile strength of the laminations, $f_{t,o}$, and the bending strength of the glulam beams, $f_m$. The ratios given in table 1 correspond to the product $k_1 \cdot k_2$ - see equ. (1) - and to the factor $k_{1,fj}$, respectively - see equ. (2).

Table 1: Relationship between bending strength of glulam beams and tensile strength of lamination or finger joint (LARSEN, 1982)

| Quality of outer lamination[1] | $\frac{f_m}{f_{t,o}}$ | $\frac{\sigma_o}{f_{t,o}}$ [2] | equivalent to |
|---|---|---|---|
| Ucl | 1.34 to 2.05 | 1.18 to 1.66 | $k_1 \cdot k_2$ |
| T 300 | 1.20 to 1.73 | 1.28 to 1.52 | |
| T 400 | 1.02 to 1.17 | 1.24 to 1.36 | |
| finger joint | 1.36 to 1.71 | 1.43 to 1.89 | $k_{1,fj}$ |

1) according to the Nordic grading system;

2) $\sigma_o$ is the bending stress when the transformed section of the glulam beam is taken into account.

The data in table 1 show a rather high variability, but the following points should be noticed:

- the lateral displacements measured during the tension tests of the laminations varied extremely; therefore, the modification factor $k_1$ is difficult to determine; the tension test according to ISO 8375 is suitable to test the tensile strength of solid timber in structural sizes. If the laminations of glulam beams are tested in this way, then the deduction of the glulam bending strength becomes problematic.

- the ratio $f_m/f_{t,o}$ in table 1 depends on the building-up of the beams. For example, a high MOE of the outer lamination and a low MOE of the second lamination causes an effective bending stress in the outer lamination which is higher than calculated by using the ordinary formula $f_m = M/W$, where M is the bending moment, and W is the section modulus of the full cross-section. Therefore the ratio $\sigma_o/f_{t,o}$ is also given in table 1.

- the depth of the beams tested was in all cases 233 mm. This comparatively small depth and consequently unequal stress distribution in the outer laminations raise the question if these ratios are of the same level in beams of high depths.

- the ratios for finger joints ($k_{1,fj}$), found by LARSEN, are high compared with those of the laminations themselves ($k_1 \cdot k_2$) because the effect of hindered longitudinal strains of weak zones does not exist in finger joints. On the other hand, finger joints may be more sensible to lateral displacements due to higher brittleness.

For establishing the factors $k_{v,1}$ and $k_{v,2}$ as well as $k_{v,3}$ the relevant coefficients of variation are needed. Therefore, a big number of tests is desirable to obtain reliable data. In table 2, these factors are listed on the basis of $k = 1.7$.

Table 2: Factors $k_{v,i} = \frac{1 - k \cdot v_1}{1 - k \cdot v_2}$

| $v_2$ \ $v_1$ | 0.10 | 0.15 | 0.20 | 0.25 | 0.30 |
|---|---|---|---|---|---|
| 0.10 | 1.0 | 0.90 | 0.80 | 0.69 | 0.59 |
| 0.15 | 1.11 | 1.0 | 0.89 | 0.77 | 0.66 |
| 0.20 | 1.26 | 1.13 | 1.0 | 0.87 | 0.74 |
| 0.25 | 1.44 | 1.30 | 1.15 | 1.0 | 0.85 |
| 0.30 | 1.69 | 1.52 | 1.34 | 1.17 | 1.0 |

LARSEN showed that the coefficient of variation depends on the grade and the method of grading of the laminations. The grading systems should therefore reduce the variability of the tensile strength. This will also lead to a smaller coefficient of variation of the glulam bending strength.

Assuming coefficients of variation of 0.10 to 0.15 for the glulam bending strength and of 0.15 to 0.30 for the lamination tensile strength, respectively, the factor $k_{v,1}$ will range from 1.11 to 1.52 (see table 2).

Thus, from table 1 and 2, and equ. (7) can be derived:

$$f_{m,k,Glulam} = (1.18 \text{ to } 1.66) \cdot (1.11 \text{ to } 1.52) \cdot f_{t,o,k}$$

$$\boxed{f_{m,k,Glulam} = (1.31 \text{ to } 2.52) \cdot f_{t,o,k}} \tag{13}$$

Assuming that the coefficients of variation, $v_{m,Glulam}$ and $v_{m,fj}$ are equal, then

$$k_{v,2} \cdot k_{v,3} = \frac{1 - k \cdot v_{m,Glulam}}{1 - k \cdot v_{m,fj}} \approx 1.0 \quad . \tag{14}$$

LARSEN |2| found, that

$$k_3 = \frac{f_{t,o,fj}}{f_{m,fj}} \approx 0.6 \quad . \tag{15}$$

Then from table 1 and equ. (11) follows:

$$f_{m,k,Glulam} = (1.43 \text{ to } 1.89) \cdot 0.6 \cdot 1.0 \cdot f_{m,k,fj}$$

$$\boxed{f_{m,k,Glulam} = (0.86 \text{ to } 1.13) \cdot f_{m,k,fj}} \tag{16}$$

Any possible volume effects are not taken into account, because the numerical values are derived from glulam bending test with a constant depth of 233 mm. Therefore, it cannot be excluded that further reductions of the coefficients in equs. (13 and 16) are necessary. Tests by EHLBECK, COLLING, GÖRLACHER |3| verified, however, equ. (16). The tensile strength of finger joints, with 239 replications, turned out to be approximately

$$f_{t,o,fj} \approx 35\ \mathrm{N/mm^2}$$

with $v_{t,o,fj} \approx 0.24$. 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 test length of about 150 mm. Hence, using these data the modification factor $k_{l,fj}$ is unity.

Bending tests with finger joints taken from the same production period as those for the tension tests proved a bending strength of

$$f_{m,fj} \approx 44.5\ \mathrm{N/mm^2}$$

with $v_{m,fj} \approx 0.14$. From this follows that

$$k_3 = \frac{f_{t,o,fj}}{f_{m,fj}} = 0.79 \quad . \tag{17}$$

Then from equ. (11) follows:

$$f_{m,k,Glulam} \approx 1,0 \cdot 0,79 \cdot 1.0 \cdot f_{m,k,fj}$$

$$\boxed{f_{m,k,Glulam} \approx 0.80 \cdot f_{m,k,fj}} \tag{18}$$

Recent bending tests from EHLBECK and COLLING |4| with glulam beams of different depth between 330 and 1250 mm and with or without finger joints in the outer tensile laminations confirmed the assumptions that

- the bending strength of glulam beams depends on the tensile strength of the outer laminations and their finger joints,
- longitudinal strains of zones with finger joints can not be inhibited by adjacent laminations because of the higher stiffness of finger joints compared with the timber,
- there is no depth effect influencing the bending strength of glulam beams (with depths $\geqq$ 330 mm) as long as the strength of the finger joints controls the ultimate load-carrying capacity.

The interrelations described by the equations (13, 16 and 18) are the basis for establishing in EUROCODE 5 |5| characteristic bending strength values depending on the strength classes of the laminations and the bending strength (in flatwise bending) of the finger joints.

## 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 %.

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