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GLUED LAMINATED TIMBER
CONTRIBUTION TO THE DETERMINATION OF THE BENDING STRENGTH OF GLULAM BEAMS

by

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1 Introduction

This paper intends to summarize the results of the extensive research work done in Karlsruhe (Germany) on the bending strength of glulam beams. Above all it is the aim of this essay to develop design rules for glulam beams under bending.
The bending strength of glulam beams is primarily governed by two properties:
- the quality of the lamellations used;
- the strength of the finger joints

This is repeatedly demonstrated and proved by numerous tests in different countries. In order to make the problem easier to understand how the bending strength of glulam beams is influenced by mixing these two properties, it seems useful to consider first of all both effects separately.

2 Glulam beams with timber failure

2.1 Influence of lamellation quality

In the first instance the bending strength of a glulam beam is described as dependent on the knot-area ratio (KAR), the density and the modulus of elasticity (MOE) of the lamellations. These parameters are usually also used for grading of the boards and assigning them to different strength classes.
The characteristic values of the tensile strength $f_{t,o,k}$ of solid structural timber, as given in prEN 338 "Structural timber-strength classes" have been derived from characteristic values of the bending strength $f_{m,k}$. The ratio $f_{t,o,k} / f_{m,k}$ is assumed to be 0,6 . Furthermore, the characteristic tensile

strength of solid timber, as given in prEN 338, is only under certain conditions applicable for determining the glulam bending strength, because when testing the tensile strength according to ISO 8375, the test specimen may deform in such a way that bending moments due to inevitable lateral displacements will reduce the calculated tensile strength. Such lateral deformations of the board are excluded when the board is part of a glulam beam and rigidly glued to the adjacent lamellations. Thus, a board being a lamellation in a glulam beam apparently has a higher tensile strength compared to the strength which is determined in line with ISO 8375. Let us call this phenomenon the "ISO-effect". In addition to this, areas of the board with a low MOE (e.g. due to knots) are relieved of high stresses when glued to another board with a higher tensile stiffness. This leads to a kind of local reinforcement and a fictive increase of the strength. Let us call this the "lamination effect".

Starting with the characteristic tensile strength $f_{t,o,k}$ of the boards, as given in prEN 338, the characteristic bending strength $f^{o}_{m,k,gl}$ of a glulam beam of 300 mm depth (we call this the "standard beam", and its values are denoted with a "0") can be determined using the following relationship [1]:

$$f^{o}_{m,k,gl} = k_{iso} \cdot k_{lam} \cdot k_{var} \cdot f_{t,o,k,lam} \qquad (1)$$

k_{iso}	factor to describe the ISO-effect;
k_{lam}	factor to describe the lamination effect
k_{var}	taking into account the different variabilities (coefficient of variation) of the glulam bending strength and the board tensile strength.

k_{iso} is not sufficiently exact known and can only be estimated by numerous comparable tests. Based on tests made by H.J. Larsen, a value of

$$k_{iso} = 1,4$$

may be assumed. For the product of $k_{lam} \cdot k_{var}$ there was also a lack of reliable values. Riberholt/Ehlbeck/Fewell [2] proposed to use the following equation:

$$k_{iso} \cdot k_{lam} \cdot k_{var} = 2,7 - 0,04 \cdot f_{t,o,k,lam} \tag{2}$$

From this, with $k_{iso} = 1,4$, we get

$$k_{lam} \cdot k_{var} \approx 1,9 - 0,03 \cdot f_{t,o,k,lam} \tag{3}$$

This value contains only the lamination effect and the effect of variability; but, this value is the basis (or the "key") to determine the characteristic bending strength of glulam beams using the characteristic tensile strength of "restrained"-lamellations. But even this "restrained" tensile strength may only be estimated, but this can be done on the basis of some hundred tension tests with 150 mm long elements taken from boards which has been performed by P. Glos in Munich. These findings can be used for simulation calculations. With various combinations of KAR, density and MOE of the lamellations the restrained tensile strength of 20000 boards of 4,50 m length was simulated according to [3]. With the same quality requirements for the lamellations the glulam bending strength was determined using a computer programme especially developed for this task [4]. This was done for the standard beam of 300 mm depth under the supposition that no failure in the finger joints can occur. Based on the simmulations, a regression analysis showed the following relationship for $k_{lam} \cdot k_{var}$

$$k_{lam} \cdot k_{var} = 1 + \frac{10}{k_{iso} \cdot f_{t,o,k,lam}} \tag{4}$$

and with eq. (1)

$$f^{o}_{m,k,gl} = 10 + k_{iso} \cdot f_{t,o,k,lam} \tag{5}$$

Assuming a value of $k_{iso} = 1{,}4$, the calculation results and eq. (5) are shown in Fig. 1. It becomes obvious, that the proposal made by Riberholt/Ehlbeck/ Fewell (cf. eq. (2) and (3) resp.) is a good approximation in the central range; but it deviates for low and high lamination quality.

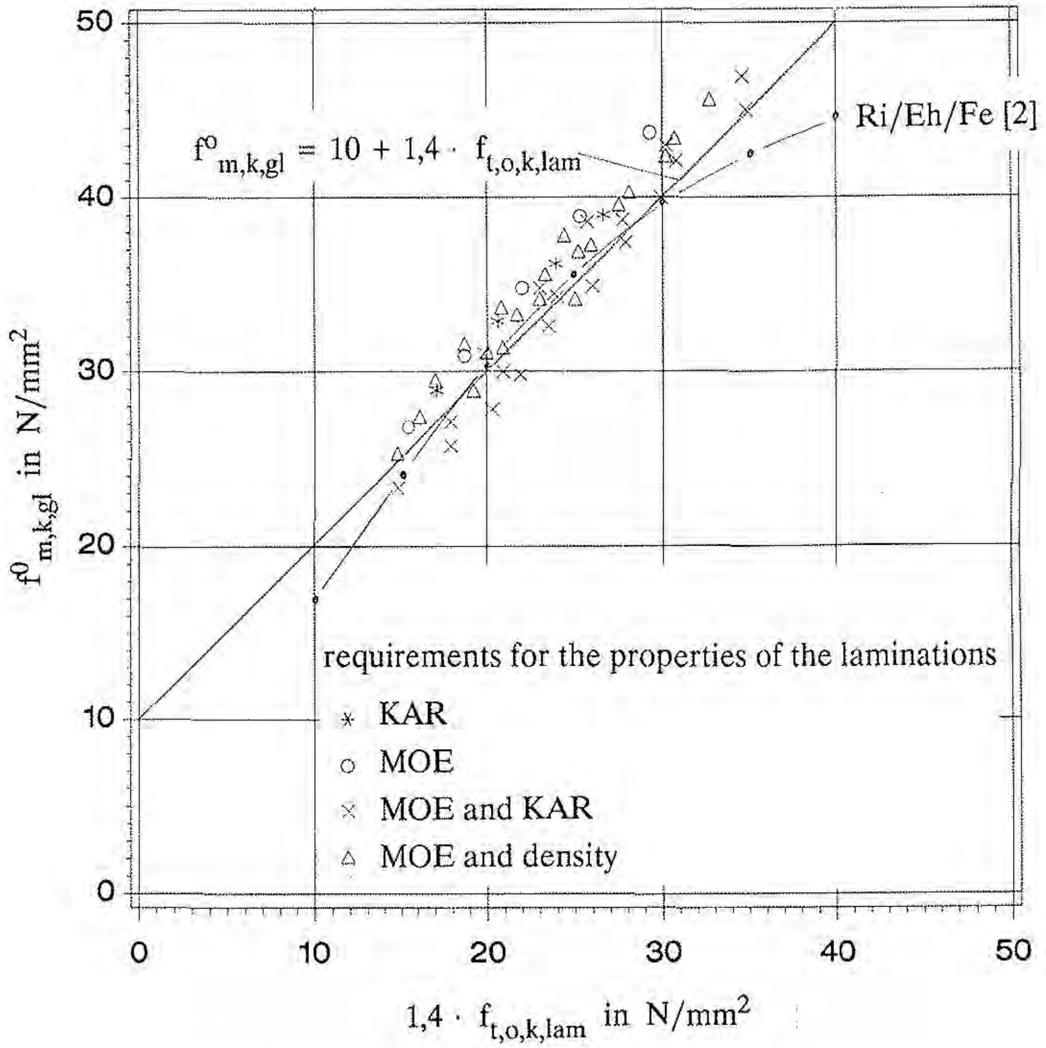

Figure 1: Characteristic bending strength $f^0_{m,k,gl}$ of standard glulam beams depending on the characteristic tensile strength $f_{t,0,k,lam}$ of the laminations

For practical application, eq. (5) can be used as a basis to determine the characteristic glulam bending strength from the characteristic strength of the boards used as lamellations.

2.2 Minimum values of timber properties to fulfil a strength class of prEN 338

Dividing the simulated restrained tensile strength by k_{iso} ($\approx 1{,}4$) we get the "free" tensile strength as given in prEN 338. Taking into consideration that these values have been derived from bending strength values multiplied by the factor of 0,6 as well as the fact that for a solid timber bending member we need other requirements than for a lamellation which is mainly stressed in tension, it was studied which limit values for KAR, MOE and density are necessary to comply with the requirements of the tensile strength of a certain strength class in prEN 338. This was done independent of any existing or agreed grading systems or grading rules. Examples for limit values are given in Table 1. In addition, the percentage of yield is specified on the basis of an extensive study at several German glulam manufacturers [5]. The advantage of machine stress grading becomes obvious.

Table 1: Examples of limit values for timber properties to comply with solid timber strength classes in prEN 338

	C18		C24		C30		C37	
	limit value	yield	limit value	yield	limit value	yield	limit value	yield
KAR<	0,67	13%	0,4	59%	0,2	28%		-
MOE>	7000	16%	10500	40%	13500	29%	16500	15%
KAR< MOE>	0,67 -	10%	0,50 9500	32%	0,35 11500	26%	0,35 14000	32%
KAR< ρ>	0,67 -	21%	0,50 420	36%	0,35 460	40%	0,35 560	3%

KAR = greatest KAR-value within one board
MOE = mean lengthwise MOE in N/mm^2 of a board
ρ = mean density in kg/m^3 of a board (moisture content $u = 12\%$)

2.3 Volume effect

Based on simulation calculations [6] the following relationship between bending strength, beam depth and beam length can be assumed for glulam beams with timber failure only:

$$f_{m,k,gl} = \left(\frac{L}{5400}\right)^{-0,07} \cdot \left(\frac{H}{300}\right)^{-0,09} \cdot f^{o}_{m,k,gl} \qquad (6)$$

with L = length, in mm

H = depth, in mm

$f^{o}_{m,k,gl}$ = characteristic glulam bending strength of the 300 mm deep standard beam.

L is assumed to be $18 \cdot H$. This relationship turned out to be almost independent of the properties of the boards.

3 Glulam beams with failure of finger-joints

3.1 General

This chapter deals only with glulam beams the failure of which are only due to failure in the finger-joints.

It was found by simulation calculations that the characteristic bending strength of standard glulam beams (beam depth H = 300 mm; ratio L/H = 18) is approximately 20 % higher than the characteristic "restrained" tensile strength of the finger-joints [6]:

$$f^{o}_{m,k,gl} = 1,20 \cdot f_{t,o,k,fj} \qquad (7)$$

Consequently, in order to guarantee a certain characteristic glulam bending strength, it is necessary to require a defined minimum stregth of the finger-joints. As it is, however, expensive to control the tensile strength during the routine quality control in the production plant, the quality control is supposed to be performed by bending tests of the finger-joints. Hence, the ratio of tensile strength to bending strength of finger joints has to be well known.

3.2 Ratio of tensile to bending strength of finger-joints

In a former study tests with 239 tension specimens and 900 bending specimens of finger-joints were performed independently from each other. The characteristic "restrained" tensile strength of randomly taken test pieces was 23,4 N/mm^2. The characteristic bending strength came to 36,3 N/mm^2. According to that the ratio is

$$f_{t,o,k,fj} / f_{m,k,fj} = 0{,}64$$

To underline this ratio, a total 700 finger-jointed lamellations were collected from four German glulam manufacturers; the one half of them was tested in tension, the other half in bending. To make sure that the test pieces are matched and comparable, the test specimens were produced following the system shown in Fig. 2.

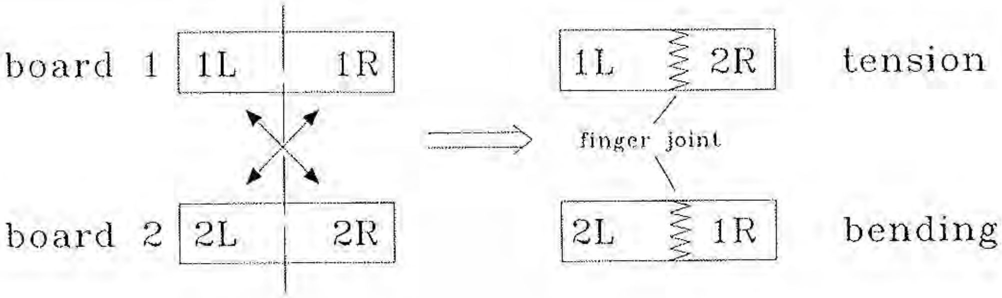

Figure 2: Matching of the test specimen

Two different finger-joint profiles, as used most frequently in Germany, were tested:

- length of the fingers 15 mm
- length of the fingers 20 mm.

Furthermore, three different series were carried out, as shown in Table 2, in order to clear up if the ratio of tensile to bending strength is dependent on the timber properties. In each test series and from each glulam plant 30 test specimens were made.

Table 2: Requirements for timber properties; tests with finger joints

series I	no requirements; random boards
series II	$11500 < \text{MOE} < 13500\ \text{N/mm}^2$
series III	$15000 < \text{MOE}$

Table 3 and 4 contain the results. The following tendencies can be recognized:

- the mean strength values of series 1 and 2 do not differ significantly;
- the variability (coefficient of variation) of the strength values from series 2 is significantly lower due to the lower variability of the timber properties;
- the mean strength values of series 3 are approximately 20 % higher than those of series 1 and 2.

Table 3: Test results; tension tests with finger joints

	plant 1 15 mm	plant 2 15 mm	plant 3 20 mm	plant 4 20 mm	15 mm	20 mm	all
series I:							
mean (MPa)	37,1	33,5	35,3	29,7	35,4	32,5	33,9
coeff. var.	0,27	0,23	0,16	0,19	0,26	0,20	0,23
N	30	27	30	29	57	59	116
series II:							
mean (MPa)	38,8	36,0	35,1	33,1	37,3	34,3	35,7
coeff. var.	0,15	0,16	0,22	0,15	0,16	0,19	0,18
N	27	29	30	28	56	58	114
series III:							
mean (MPa)	48,8	42,9	42,7	34,6	45,9	38,9	42,5
coeff. var.	0,17	0,14	0,16	0,11	0,17	0,18	0,19
N	28	28	29	25	56	54	100

Table 4: Test results; bending tests with finger joints

	plant 1 15 mm	plant 2 15 mm	plant 3 20 mm	plant 4 20 mm	15 mm	20 mm	all
series I:							
mean (MPa)	51,1	48,2	51,6	45,2	49,6	48,7	49,2
coeff. var.	0,17	0,14	0,16	0,15	0,16	0,17	0,16
N	28	30	30	25	58	55	113
series II:							
mean (MPa)	54,7	48,4	54,2	47,0	52,1	50,7	51,3
coeff. var.	0,09	0,09	0,12	0,10	0,11	0,13	0,12
N	29	21	30	29	50	59	109
series III:							
mean (MPa)	66,3	58,9	63,1	54,0	62,6	59,0	60,8
coeff. var.	0,09	0,10	0,13	0,07	0,11	0,13	0,13
N	28	28	30	25	56	55	111

Table 5 shows the ratios $f_{t,o,k,fj} / f_{m,k,fj}$ assuming a normal Gauss distribution[1]. The individual values range from 0,50 to 0,68 with a mean of 0,60.

Table 5: Ratio $f_{t,o,k,fj} / f_{m,k,fj}$, assuming a Gauss-distribution

	plant 1 15 mm	plant 2 15 mm	plant 3 20 mm	plant 4 20 mm	15 mm	20 mm	all
series I	0,55	0,57	0,68	0,60	0,55	0,63	0,58
series II	0,63	0,64	0,50	0,64	0,64	0,59	0,61
series III	0,62	0,65	0,63	0,59	0,65	0,60	0,60

A number of test specimens failed - at least partly - outside the finger joint area. Especially in the tension tests, knots near the grips showed a great influence. Therefore the tests were reevaluated, excluding those test specimen with unsuitable failure mode. This leads to higher tensile strength values of the different series, whereas the bending strengths did not change greatly. Table 6 shows the ratios $f_{t,o,k,fj} / f_{m,k,fj}$ for test specimen with a failure of at least 80% in the area of finger joints.

Table 6: Ratio $f_{t,o,k,fj} / f_{m,k,fj}$ for test specimen with at least 80% failure in the area of finger joints

	plant 1 15 mm	plant 2 15 mm	plant 3 20 mm	plant 4 20 mm	15 mm	20 mm	all
series I	0,61	0,58	0,73	0,69	0,59	0,73	0,65
series II	0,68	0,70	0,52	0,67	0,72	0,61	0,63
series III	0,61	0,70	0,70	0,59	0,65	0,62	0,61

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[1] A determination of characteristic strength values on the basis of a Student-t- or Weibull-distribution as well as by "counting" showed no significant influence on the ratios $f_{t,o,k,fj} / f_{m,k,fj}$

On the basis of this, a ratio of

$$f_{t,o,k,fj} / f_{m,k,fj} \approx 0,65$$

may be assumed.
Deviating from the tests made by P. Glos ("restrained" tensile strength), for simplicity the tension tests reported here were carried out by using the test set-up as shown in Fig. 3.

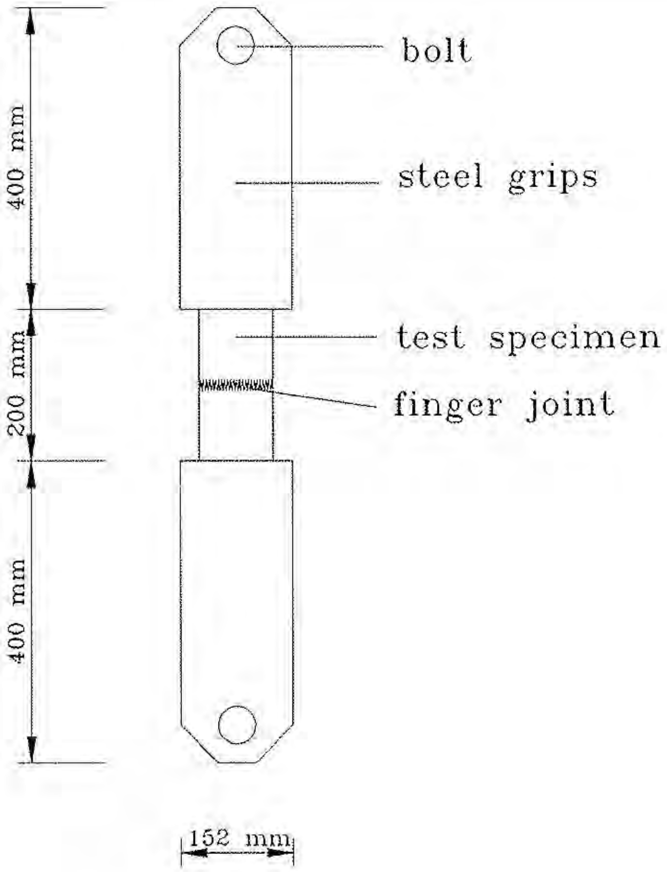

Figure 3: Test set-up for tension tests

Due to that, lateral deformations reducing the tensile strength (compare with ISO-effect!) can not completely be excluded. Therefore, it seems to be justified to use an all-over ratio of

$$f_{t,o,k,fj} / f_{m,k,fj} \approx 0{,}7 \qquad (8)$$

(see also [7]).
From eq. (7) now results:

$$f^{o}_{m,k,gl} = 0{,}84 \cdot f_{m,k,fj} \qquad (9)$$

This value of 0,84 may be increased if the type of loading is taken into account. A value of 1,04 may be used for uniformly distributed loads instead of 1,00 for two single loads applied at a distance of L/3 from the beam supports ([7]). Then:

$$f^{o}_{m,k,gl} = 0{,}87 \cdot f_{m,k,fj} \qquad (10)$$

From this the requirement can be derived that

$$f_{m,k,fj} \geq 1{,}15 \cdot f^{o}_{m,k,gl} \qquad (11)$$

i.e., the characteristic bending strength of the finger-joints shall be at least 15% higher than the characteristic bending strength of the standard glulam beam.

3.3 Minimum values of timber properties to fulfil the requirements

In an extensive study on the bending strength of finger-joints [8] the following regression equations were found to describe the bending strength of finger-joints as depending on the MOE and on density of the laminations:

$$f_{m,fj} = 27{,}58 + 0{,}0019 \cdot E_{min} \qquad (12)$$

$$f_{m,fj} = 4{,}26 + 0{,}11 \cdot \rho_{12,min} \qquad (13)$$

The density $\rho_{12,min}$ in kg/m^3 and the modulus of elasticity E_{min} in MPa, respectively, are the lower value of the two adjacent (jointed) boards. Taking into consideration the results of a study on the board material used in German glulam factories [5], examples of limit values for timber properties to comply with finger joint requirements of some glulam strength classes are given in Table 7. This table contains also data on the percentage of yield to be expected.

Table 7: Examples of limit values for timber properties to comply with finger joint requirements of some glulam strength classes

glulam strength class	LH 25		LH 30		LH 35		LH 40	
$f_{m,k,fj} >$	27,5		34,5		40		46	
	limit value	yield	limit value	yield	limit value	yield	limit value	yield
$\rho >$	none	6 %	390	23 %	440	50 %	510	22%
MOE >	none	5 %	9000	31 %	12000	37 %	15000	27 %

ρ = mean density in kg/m^3 (moisture content u = 12%)
MOE = mean lengthwise MOE in N/mm^2

3.4 Volume effect

Fig. 4 contains the characteristic glulam bending strength related to the strength value of the standard beam with failure at the finger-joints over the beam length based on calculations in [6].

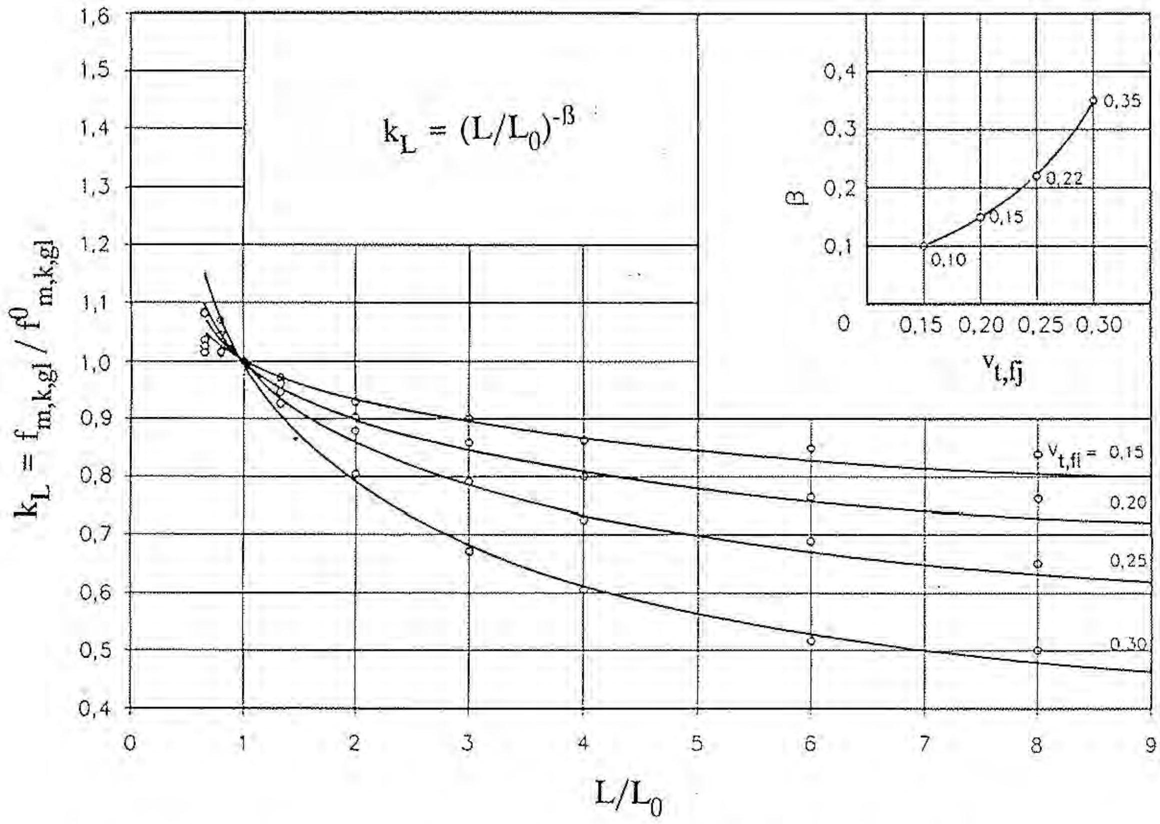

Figure 4: Length-effect for glulam beams with failure due to finger joints

The figure shows curves for different coefficients of variation $v_{t,fj}$ of the finger-joint's tensile strength. It is obvious that the coefficient of variation is of evident importance:

- with increasing c.o.v. the influence of the volume effect is also increasing.

When there is only a visual grading used for the lamellations (i.e. when density and MOE are unknown), then the c.o.v. can be expected at a level of approximately 0,20. Then, the exponent to take into account the volume effect results in 0,15 (see also [7]).

The strength of finger-joints also depends significantly on production effects. Therefore, it should be possible to reduce the variability of the strength of finger-joints considerably by tightening up the production requirements (e.g. routine quality control). If the requirements recommended before (see clause 3.2) are fixed, it can be expected that the glulam producers will aim at a small variability of the finger-joints bending strength, because then the characteristic value will increase considerably.

In view of a machine grading based on density and/or MOE it is possible to reduce the c.o.v. of the strength values (see table 3 and 4). Therefore, it seems to be adequate to lower the exponent in the volume effect. It is proposed to use the following formula:

$$f_{m,k,gl} = \left(\frac{H}{300} \cdot \frac{L}{5400} \right)^{-0,10} \cdot f^{o}_{m,k,gl} \qquad (14)$$

with H and L in mm.

This equation is very close to that used for glulam beams with timber failure only (eq. 6).

4 Conclusion

It can be summarized that for aiming at certain glulam strength classes the minimum requirements for the lamellations and the finger-joints, as given in Table 8, may be used.

Table 8: Requirements to comply with some glulam strength classes

glulam strength class	LH 25	LH 30	LH 35	LH 40
strength class of the laminations	C 18	C 24	C 30	C 37
requirements due to finger joints:				
ρ >	none	390	440	510
MOE >	none	9000	12000	15000

ρ = mean density in kg/m^3 (moisture content u=12%)
MOE = mean lengthwise MOE in N/mm^2

The influence of the beam depth and the beam length can be taken into account by using the eq. (14).

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size effect

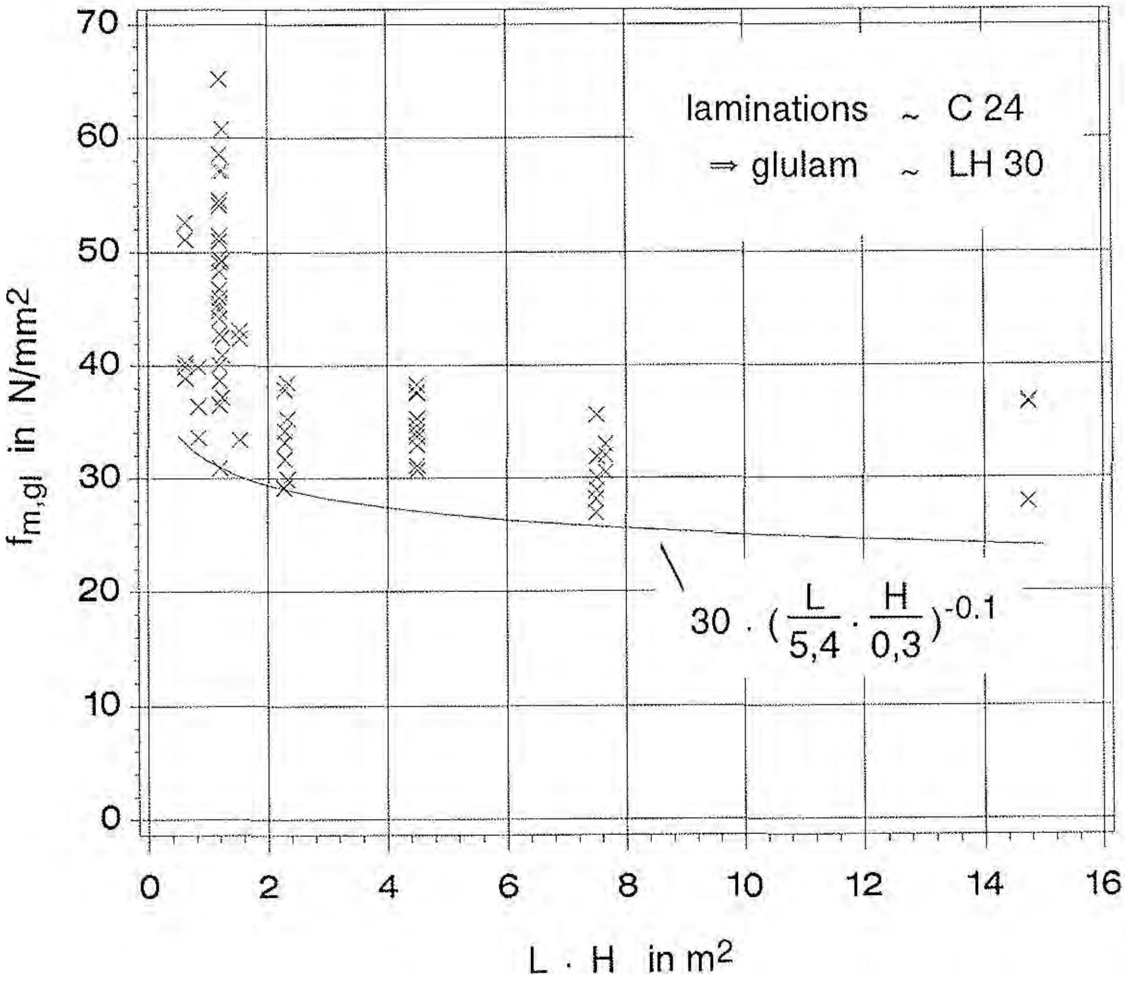

Figure 5: Test results; beams with timber failure and failure in finger joints