ESTIMATION OF THE EFFECT OF DIFFERENT GRADING CRITERIONS ON THE BENDING STRENGTH OF GLULAM BEAMS USING THE "KARLSRUHE CALCULATION MODEL"

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1 The "Karlsruhe calculation model"

1.1 General

In 1980 Foschi and Barrett developed a model for the determination of the bending strength of glulam beams |1|. In that model the laminations are divided into cells of depth t and width W, where t and W are the thickness and the width of the lamination, respectively. Each cell is randomly assigned a density and a knot diameter from the knot frequency data of the lamination quality in question. Subsequently each cell is assigned a modulus of elasticity (MOE) and a strength value.

With these data the strength of the beam is calculated by using a linear finite element method and a weakest link failure criterion.

Because very limited data were available for the strength of end joints, the effects of finger joints on the strength of glulam beams were not considered in this model.

The model of Foschi/Barrett initiated the development of the "Karlsruhe calculation model" |2|. This model is subdivided into two computer programmes: a simulation-programme and a finite-element-programme.

1.2 The simulation programme

The scope of this simulation programme is to simulate the built-up of a glulam beam.

1.2.1 Location of the finger joints

The bearing capacity of glulam beams is strongly affected by the strength of the finger joints. Therefore it is very important to know how often a finger joint occurs in the high-stressed zones of the beam. This frequency of occurence is governed by the lengths of the jointed boards.

Larsen |3| evaluated a great quantity of boards delivered to plants and found for boards with a width of 100 mm a mean length of 4,30 m with a standard deviation of 0,70 m.

In a research project |4| the spacing of the finger joints in glulam beams was measured in two manufacturing plants. The results are shown in fig. 1 and 2. These figures show, that the distances between finger joints (= board lengths) in a glulam beam may be classified into two groups:

- the first group consists of boards, which are used unshortened, whereas
- the second group consists of shorter boards, from which defects (mainly knots) are cut off.

The percentage of each group depends on the grading practice of the manufacturer and the quality of the wood material. At firm A, the part of unshortened boards is predominant (about 85 %), whereas at firm B only about 30 % of the boards were unshortened.

These reflections illustrate, that it is rather unlikely to specify a statistical distribution, which is valid for all glulam manufacturers.

Hence, the strength of glulam beams may differ from manufacturer to manufacturer, not only as far as the strength of finger joints is concerned, but also their frequency of occurrence.

On purpose to use the simulations described in section 2, the results of fig. 1 and 2 were summarized (see fig. 3). The calculations were performed, assuming, that one half of the boards is built - in unshortened, with a mean length of 4,30 m and a standard deviation of 0,70 m, whereas the other half of the boards, from which defects are cut off, has a mean length of 2,15 with a stand. dev. of 0,50 m (see fig. 3).

1.2.2 Allociation of density and KAR-values

Glos |5| gives a mean ovendry-density of 430 kg/m^3 with a standard deviation of 50 kg/m^3 for European whitewood. From this distribution each board is randomly assigned a characteristic density, around which the densities of the cells may alternate. But since the effect of the variation of the density within a board will certainly be concealed by the variation of the strength and stiffness properties, the density of a board is assumed to be constant (cf. |2|).

The assignment of knot data is not carried out totally at random from the knot frequency data of the lamination in question (cf. model of Foschi/Barrett). Specific investigations |6| with more than 450 boards made it possible to assign knot values, taking into account the regularities due to the growth behaviour of the tree (characteristic knot diameter, distance between knots etc.).

1.2.3 Determination of the modulus of elasticity (MOE)

Based on the given values of the density and the total KAR- values according to the ECE-rules |7|, the estimated MOE of each cell may be calculated by the regression equations given in table 1 (see also |2|). These regression equations were determined by numerous tests (|5|) with test specimen having a free length of 150 mm, approximately, which is equivalent to the defined length of one cell.

As two cells with equal density and KAR-value may have different strength and stiffness properties, a value, taken at random from the residue of the regression equation, may be added to the calculated value of MOE. Examinations |8| of 640 board sections from 100 boards showed, however, that the variation of the MOE within one board is lower than is expected by the residue of the regression equation. This may also be explained by the growth behaviour of a tree. The consideration of these results led to a further improvement of the simulation programme.

1.2.4 Determination of the resistance

Based on the values of KAR, density and/or MOE the estimated strength of each cell is calculated by the regression equations given in table 2. These equations were determined by the same tests as mentioned in section 1.2.3 (cf. table 1). 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. As lateral displacements of the laminations are prevented, when the laminations are part of a glulam beam, these regression equations apply very well to the conditions of a 150 mm-board section in a glulam beam. Thus, these regression equations need not be corrected in order to take into account the effect of hindered lateral displacements (cf. |9|), as it is necessary in the model of Foschi/Barrett.

A probably lower variability of the strength properties within one board can actually not be considered, because no data are available in this field. This topic will be investigated in a subsequent research project, because an additional improvement of the simulation programme may be expected: mainly the bearing capacity of glulam beams with high- quality laminations is actually underestimated by the "Karlsruhe calculation model" because of the assumption of a high variability of the strength properties within one board.

1.2.5 Possible variations of the simulation programme

Within the simulation programme it is possible to prescribe some criterions, which must be fulfilled by the simulated laminations:

- maximum KAR-value,
- minimum density,
- MOE of boards or lamellae,
- minimum tensile strength.

Hence, it is possible to investigate the effect of different ways of wood grading on the bearing capacity of glulam beams (see section 2). Moreover, it is possible to estimate the strength of test beams especially those from which some properties (density, knot distribution, MOE of boards) are known from preliminary investigations (see section 1.4). Furthermore it is possible to vary the strength of finger joints, so that different qualities of finger joints or variations of the strength due to production can be taken into account.

1.3 Finite element programme

The finite element programme takes into account the non-linear behaviour of wood in compression by a linear elastic-linear plastic stress-strain relationship. Furthermore, the "Karlsruhe calculation model" has a more detailed failure criterion than the weakest link failure criterion of Foschi/Barrett's model:
after a failure of a cell in the tension zone of the beam, it is checked if the adjacent cells are able to resist the resulting load restorage. The bearing capacity of the glulam beam is reached, if two cells fail simultaneously at the same load level or if two superimposed cells fail in succession.

1.4 Verification of the calculation model by tests

In |4| more than 40 glulam beams were tested, with depths ranging from 167 mm up to 1250 mm. The bending strength of nine of them was estimated by the "Karlsruhe calculation model". The beam configuration, test set-up and the test results are given in table 3. These beams had no finger joints in the two outer tension laminations of the high stressed region (between the acting forces F), except beams III.2 and III.3, and in both cases these finger joints were responsible for the failure of the beam.

The characteristics of the two outer laminations (density, MOE, knot distribution) of each test beam were well known.

The bending strength of a glulam beam is strongly influenced by the tensile strength of the finger joints. The strength of finger joints is varying and may differ from manufacturer to manufacturer. But also within one manufacturer's plant the strength of the finger joints varies dayly. Therefore, the tensile strength of 21 finger joints, taken at the day of the production of the glulam beams, was determined with the test set-up described in section 1.2.4 (i.e. a non-ISO tension test). These tests submitted a mean tensile strength of 32,7 N/mm^2, with a standard deviation of 6,8 N/mm^2. These specific strength values were used to estimate the bearing capacity of the test beams.

A total of 30 simulations was performed for each test beam. Each simulation run specifies a corresponding cause of failure (knot or finger joint) and based on the frequency of each failure cause, it is possible to predict the failure mode of the beam during the test.

The results of these simulation calculations are shown in fig. 4-6, and it is recognized, that the failure behaviour of all test beams has been well predicted by the model. A comparison of the test results with the mean simulation results (under consideration of the actual failure mode) is shown in fig. 7. The mean simulation results differ less than 10 % from the test results, so that a very good agreement can be stated.

2 Effect of various grading criterions on the bending strength of glulam beams

2.1 Determination of the strength properties of finger joints

The average quality of finger joints produced by German manufacturers is basis of the following calculations. The corresponding strength properties (mean tensile strength 34,8 N/mm^2, standard deviation 8,4 N/mm^2) were determined by a total of 239 tension tests with finger joints, which were taken at random from 18 German manufacturers (see |2|). Each finger joint consisted of two arbitrary boards with arbitrary density. The resulting regression equations (see table 1 and 2) refer to the lower density of the two jointed boards.

During the simulations, however, a minimum density or a minimum MOE was required in some cases, in order to simulate machine grading. Therefore, the test restults of the finger joints were evaluated once more, in order to investigate the strength properties of more "homogeneous" finger joints, i.e. when boards with similar wood properties are used. In fig 8 the results are shown for finger joints consisting of boards with densities differing not more than 50 kg/m^3 from each other. A comparison with the general regression equation (cf. table 2) shows, that neither a higher level nor a lower variance can be attained.

This may be explained by the fact, that the strength of finger joints is to a great extent controlled by production-dependent factors which may hardly be considered in the calculation model. Further investigations in this field are planned in a subsequent research project.

During the simulation calculations described as follows, the regression equations of tables 1 and 2 are used for all finger joints, independently of the simulated grading procedure.

For the wood cells themselves, the influence of different grading criterions is already included in the regression equations, so that no further investigation in this field is necessary.

2.2 Calculation results and discussion

A total of 7 different wood grading methods - visual grading (3 x), machine grading (2 x) and combined visual/machine grading (2 x) - was investigated. The requirements raised for the two outer tension laminations are given in table 4. 30 simulations were performed for each grading method. The series of the seven grading methods (classes of table 4) was calculated three times in total, including the following variations:

Series Ⓐ :
- distances between finger joints according to Larsen |3| (mean value 4,30 m, stand. dev. 0,71 m)
- quality of finger joints, as produced on average by German manufacturers (mean tensile strength 34,8 N/mm², stand. dev. 8,4 N/mm²)

Series Ⓑ :
- distances between finger joints according to section 1.2.1 (smaller distances due to the cutting off of weak zones)
- quality of finger joints as in series Ⓐ

This series was to investigate the effect of more frequent occurrence of finger joints.

Series Ⓒ :
- distances between finger joints as in series Ⓑ
- 20 % higher tensile strength of finger joints than in series Ⓐ and Ⓑ

This series was to investigate the effect of higher strengths of finger joints on the bending strength of glulam beams.

When evaluating the simulation results it was differentiated, whether a knot or a finger joint was responible for the beam's failure. The calculation results are shown in fig. 9 to 11. From fig. 9 and 10 can be seen, that a more frequent occurrence of finger joints in the high stressed zone of a glulam beam leads to a higher percentage of beam failures due to finger joints: ~ 65 % in series Ⓐ in comparison to ~ 75 % in series Ⓑ . The bending strength of the beams of series Ⓑ is consequently more strongly determined by the (lower) strength of the finger joints; this leads to a decrease of the (mean) bending strength of the beams in question.

An increase of the tensile strength of the finger joints (series Ⓒ) leads to a decreasing percentage of beam failures due to finger joints (~ 50 %), and thus, to a higher bending strength of the beams. Series Ⓑ and Ⓒ show, that a stronger visual grading (cf. class Kl II → class KAR) leads only to a certain degree to higher bending strengths of the beams: the higher wood quality can not be taken advantage of, because of the higher percentage of the beam failure due to finger joints. Only machine grading on the basis of wood density (cf. class RHO) or MOE (cf. class EMO) leads to an increase of the strength of finger joints and thus to a higher bending strength of the beams in coincidence with a lower percentage of beam failures due to finger joints. Furthermore, the variance of the bending strength of these beams is reduced, because the strength of the wood and the strength of the finger joints of these beams are fitted to each other.

A grading method taking into account only one grading criterion has the disadvantage, that the strength - increasing effect of a high density may as well be compensated by a big knot as the strength-increasing effect of a small knot by a low density. Consequently, only a combined visual/machine grading is able to guarantee high wood-strengths with a satisfactory reliability. From fig. 10 (series Ⓑ), however, follows that these high wood strengths do not automatically lead to high bending strengths of glulam beams, because the actual mean quality of the finger joints does not make use of the possible advantages of an improved grading method. This is only possible by using outstanding good finger joints (see series Ⓒ , fig. 11).

Hence, the profit of a grading method also depends on the balance of the two factors "strength of wood" and "strength of finger joints".

The calculation results were also evaluated in order to investigate the effect of different grading methods on the bending strength of glulam beams with wood failure and failure due to finger joints, respectively.

The results for beams with wood failure are given in table 5. The mean bending strength of the beams with wood failure tested in |4| amounted to 33,7 N/mm^2 with a stand. dev. of 3,5 N/mm^2. These beams belonged to the "Güteklasse II" according to the German grading standard DIN 4074 and are comparable with the simulated class Kl. II. The comparison with the strength values of this class (mean bending strength 34,4 N/mm^2, stand. dev. 3,5 N/mm^2 of table 4) points out a very good agreement between simulation results and test results, as stated in section 1.4.

A stronger visual grading (class Kl. I and KAR resp.) leads to an increase of the bearing capacity of approximately 6 % and 8 %, respectively, as long as the beams fail in the wood.

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Using machine grading on the basis of density (class RHO) and MOE (class EMO), 7 and 12 %, resp., higher bending strengths can be expected, assuming the same knot values as in class Kl. II.

A further increase of the bending strength may only be reached by a combined visual/machine grading, that is nearly 20 % in case of classes KARHO and KAREMO compared with class Kl. II. Due to the lower variance in class KAREMO, the grading based on knot size and MOE seems to be better because of higher characteristic bending strength values (5th percentile).

The estimated mean bending strength of 41,0 N/mm^2 for class KAREMO seems to be somewhat low. This may partly be explained by the fact, that the determination of the strength values was performed with the total residue of the regression equations (see table 2). It might be expected that the estimated strength values for glulam beams will increase, if a lower variation of the strength within one board is allowed in the simulation calculation. This will take effect especially for beams with high quality laminations, such as class KARHO and KAREMO, for instance.

The calculation results for beams with failure due to finger joints are given in table 6. The bending strength of glulam beams with failure due to finger joints is obviously not affected by a more or less strong visual grading - rules, because the strength values of the classes Kl. I, Kl. II and KAR are all on the same level. Only a better wood quality (higher density or MOE) leads to higher strength values (for the finger joints as well as for the glulam beams in question). A stronger visual grading is not reflected in the strength values of the glulam beams with failure due to finger joints (cf. RHO - KARHO and EMO - KAREMO).

A comparison of the tensile strength of the finger joints with the corresponding bending strength of the glulam beams points out, that both strength values are in the same order. Tests of |4| confirm the following rough estimation: "the bending strength of glulam beams with failure due to finger joints is equal to the (non-ISO) tensile strength of the finger joints in question".

3 Summary and outlook

The effect of several methods of wood grading on the bending strength of glulam beams has been investigated using the "Karlsruhe calculation model". These calculations demonstrated the following tendencies:

- the bending strength of glulam beams is affected by two partly independent factors: the strength of wood (including knots) and the strength of finger joints;
- a stronger visual grading does not affect the strength of finger joints;
- a stronger visual grading leads to a higher percentage of beam failures due to finger joints, so that the higher wood strength may only be taken advantage of, if the strength of the finger joints is high enough;
- the outcome of a grading method depends on the balance of these two influencing factors. The increase of only one factor leads to the fact, that the bending strength of the glulam beam is determined to a higher extent by the "weaker" factor;
- the bending strength of glulam beams with failure due to finger joints is equal to the (non-ISO) tensile strength of the finger joints themselves;

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- the probability of failure due to finger joints increases with the number of finger joints in the high stressed region of the beam;
- the cutting off of weak zones (e.g. knots) in a board, leads, if ever, only partly to higher strength values for glulam beams, because one weak zone (knot) is replaced by another one (finger joint).

The "Karlsruhe calculation model" allowed to estimate the effects of various methods of timber grading on the bending strength of glulam beams. There are still some open questions, which will be investigated in a continuing research project. The purpose of this next project is to develop a proposal for an improved design method for glulam beams, taking into account the kind of timber grading - including the requirements raised to the laminations, i.e. KAR-value, density, MOE - as well as the quality of the finger joints.

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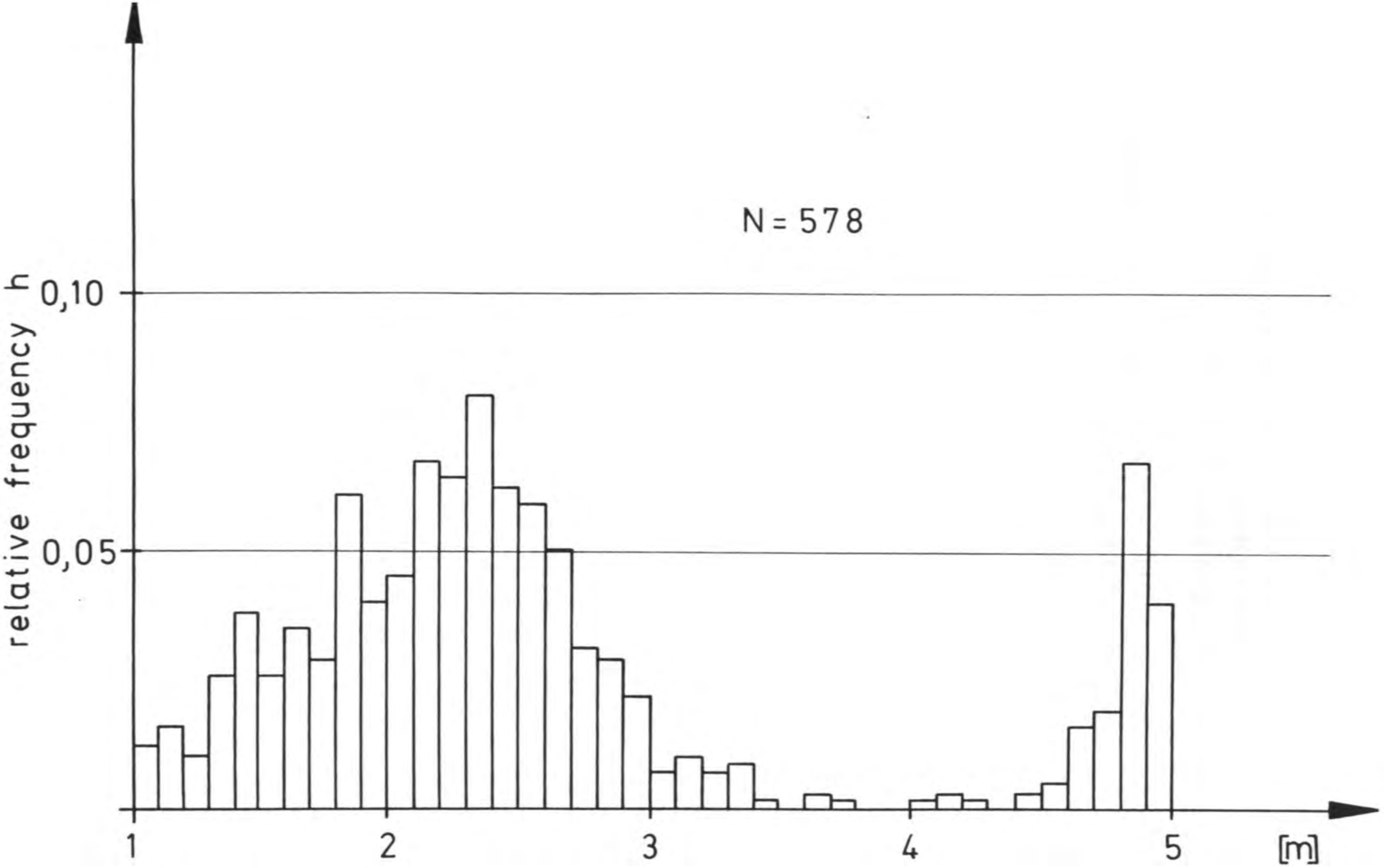


Fig. 1: Distance between finger joints, manufacturer A

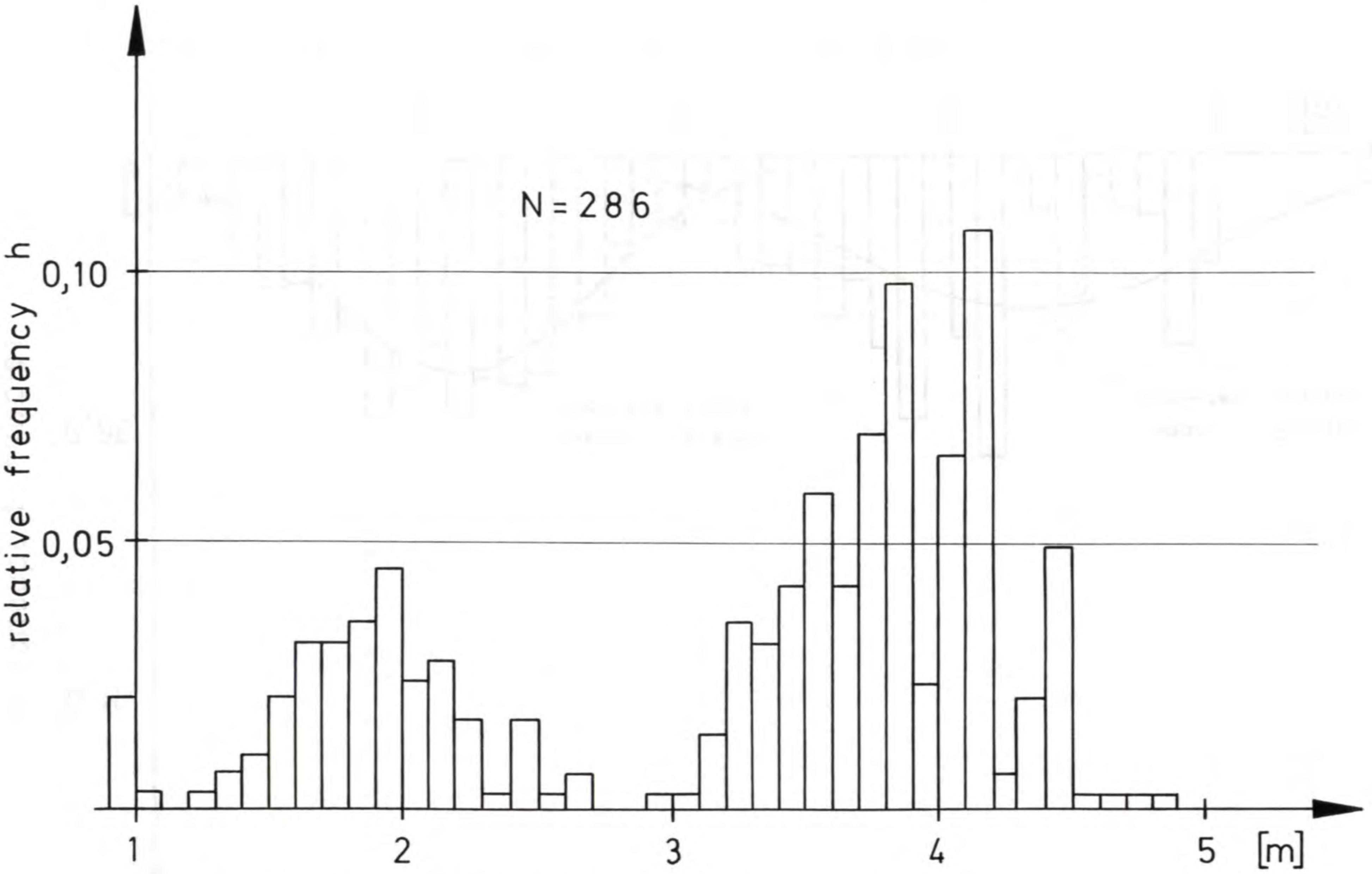


Fig. 2: Distance between finger joints, manufacturer B

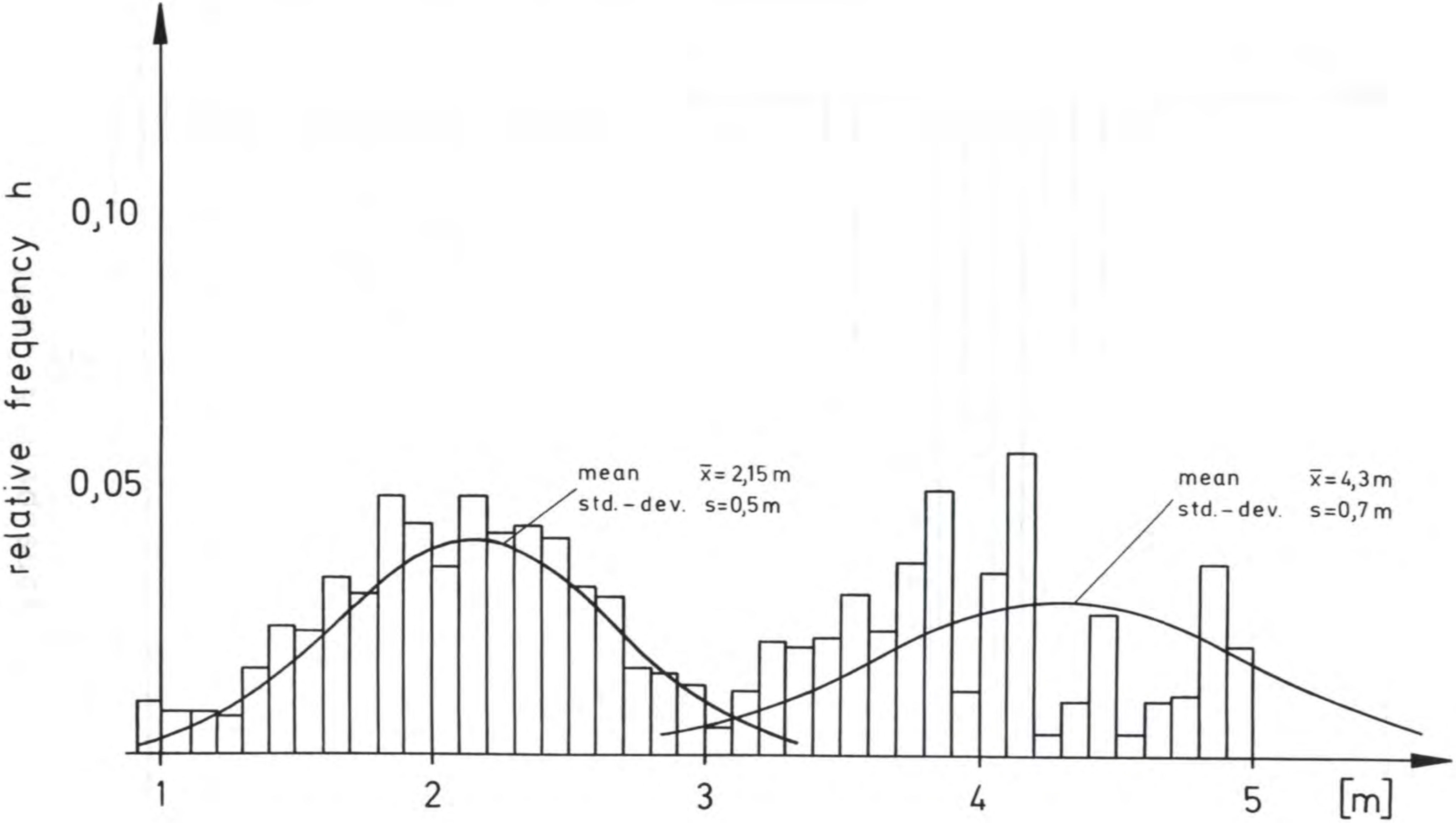


Fig. 3: Distance between finger joints, manufacturer A and B

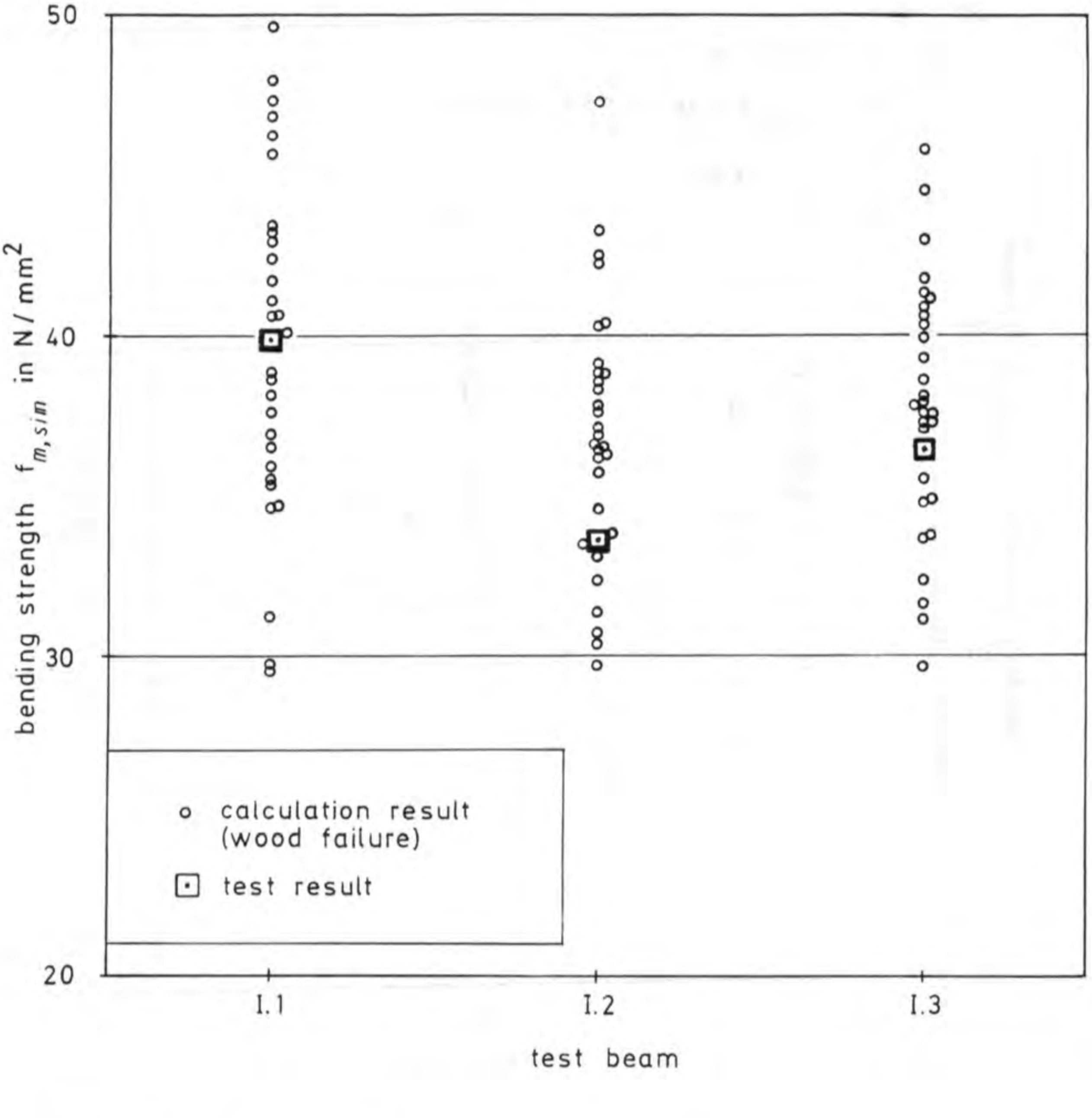


Fig. 4: Calculation results, series I

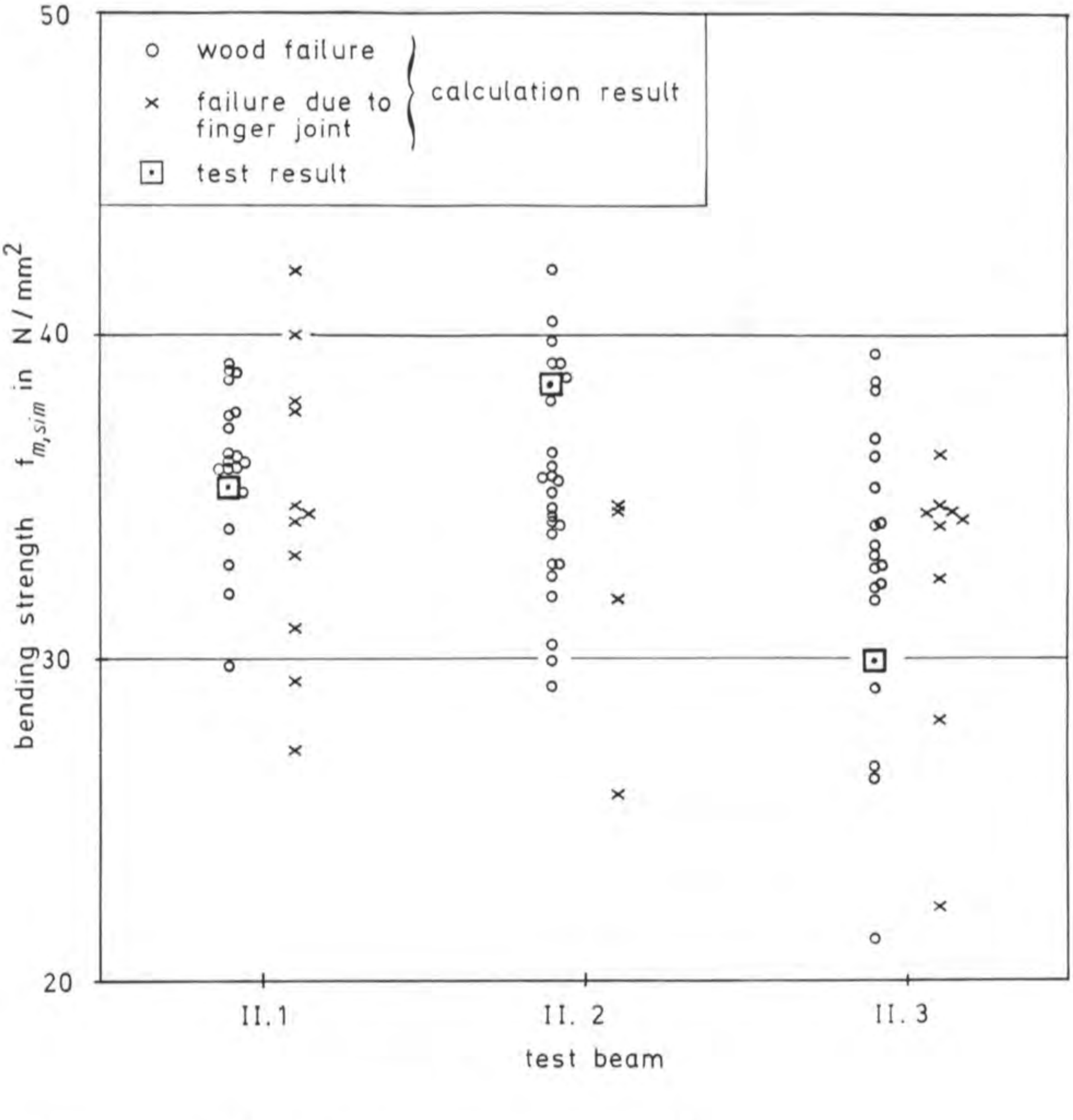


Fig. 5: Calculation results, series II

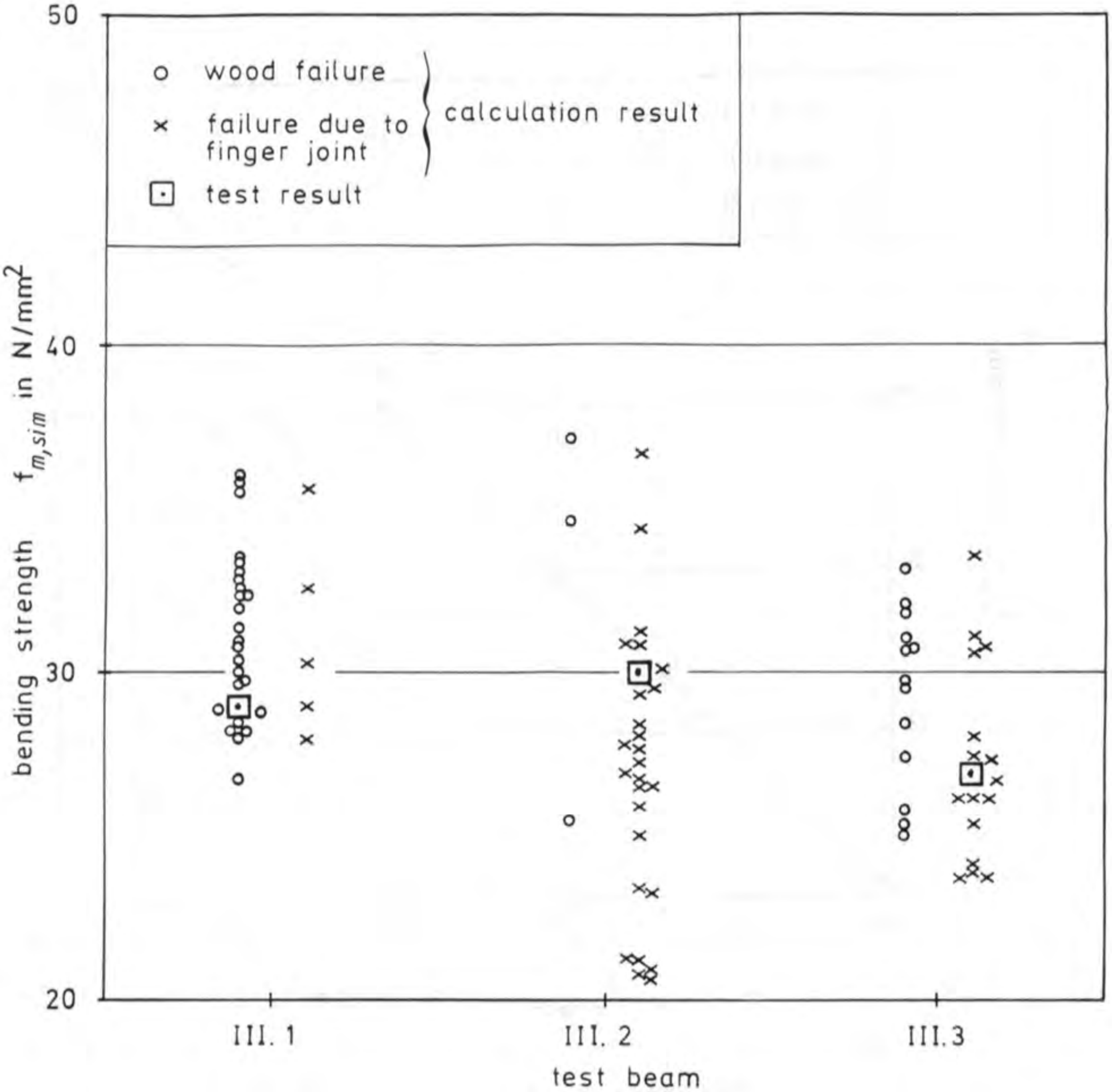


Fig. 6: Calculation results, series III

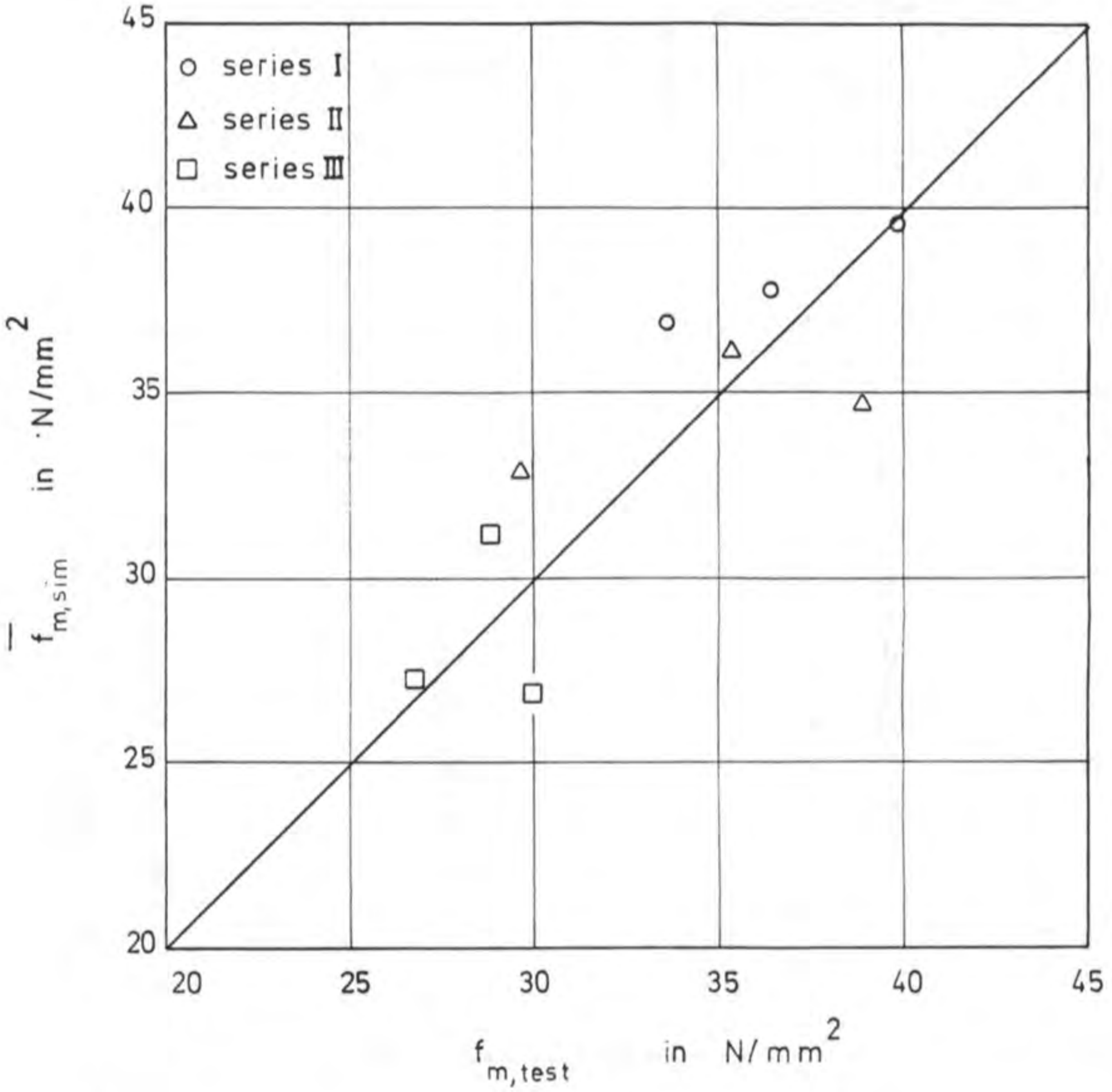


Fig. 7: Comparison of mean calculated bending strengths ($\bar{f}_{m,sim}$) with test results ($f_{m,test}$)

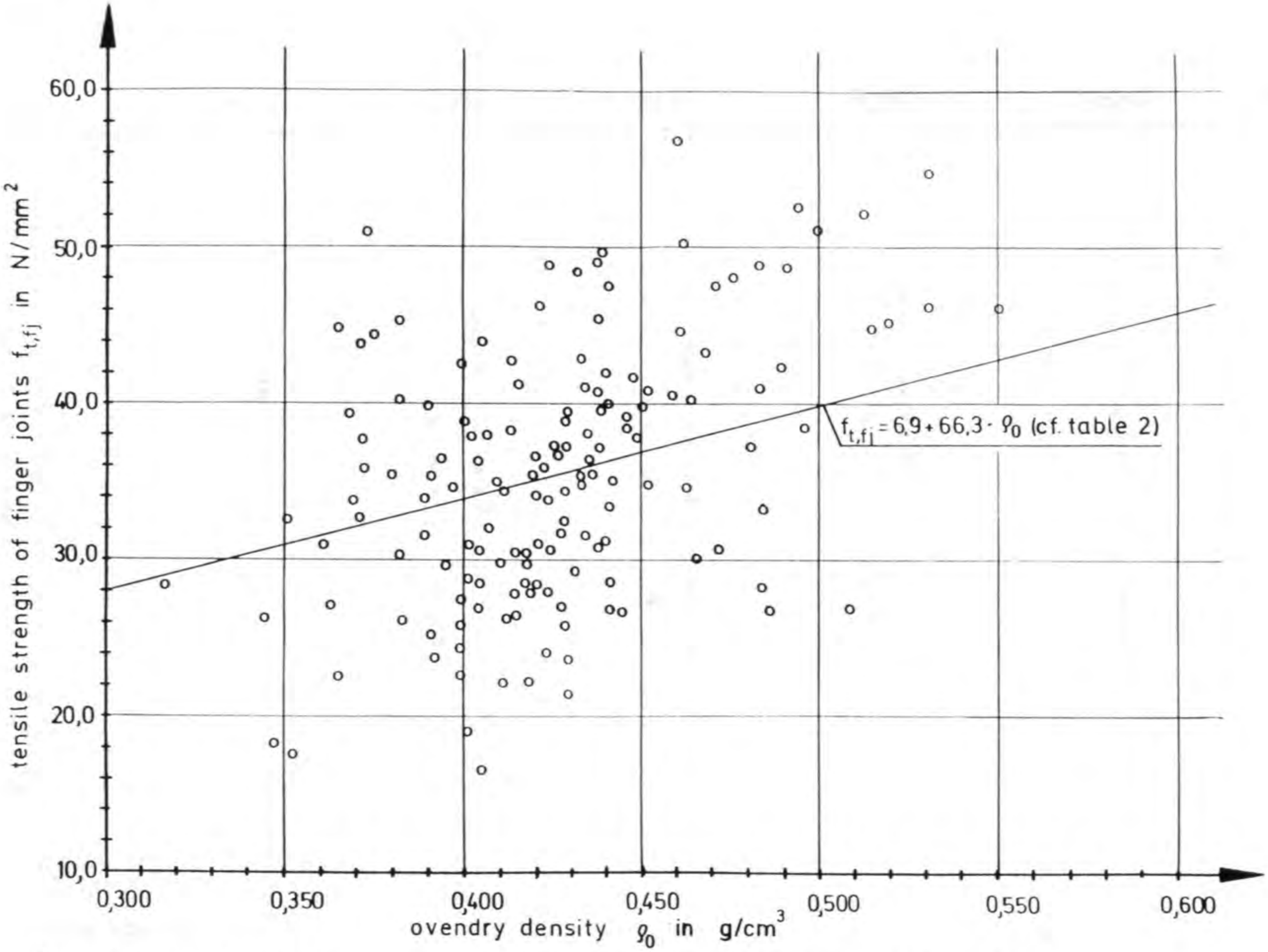


Fig. 8: Relationship between tensile strength of finger joints ($f_{t,fj}$) and the lower oven-dry density ϱ_0 of the jointed boards ($\varrho_0 = \min(\varrho_{0,left}; \varrho_{0,right})$ and $\varrho_{0,left} = \varrho_{0,right} \pm 0{,}05 g/cm^3$)

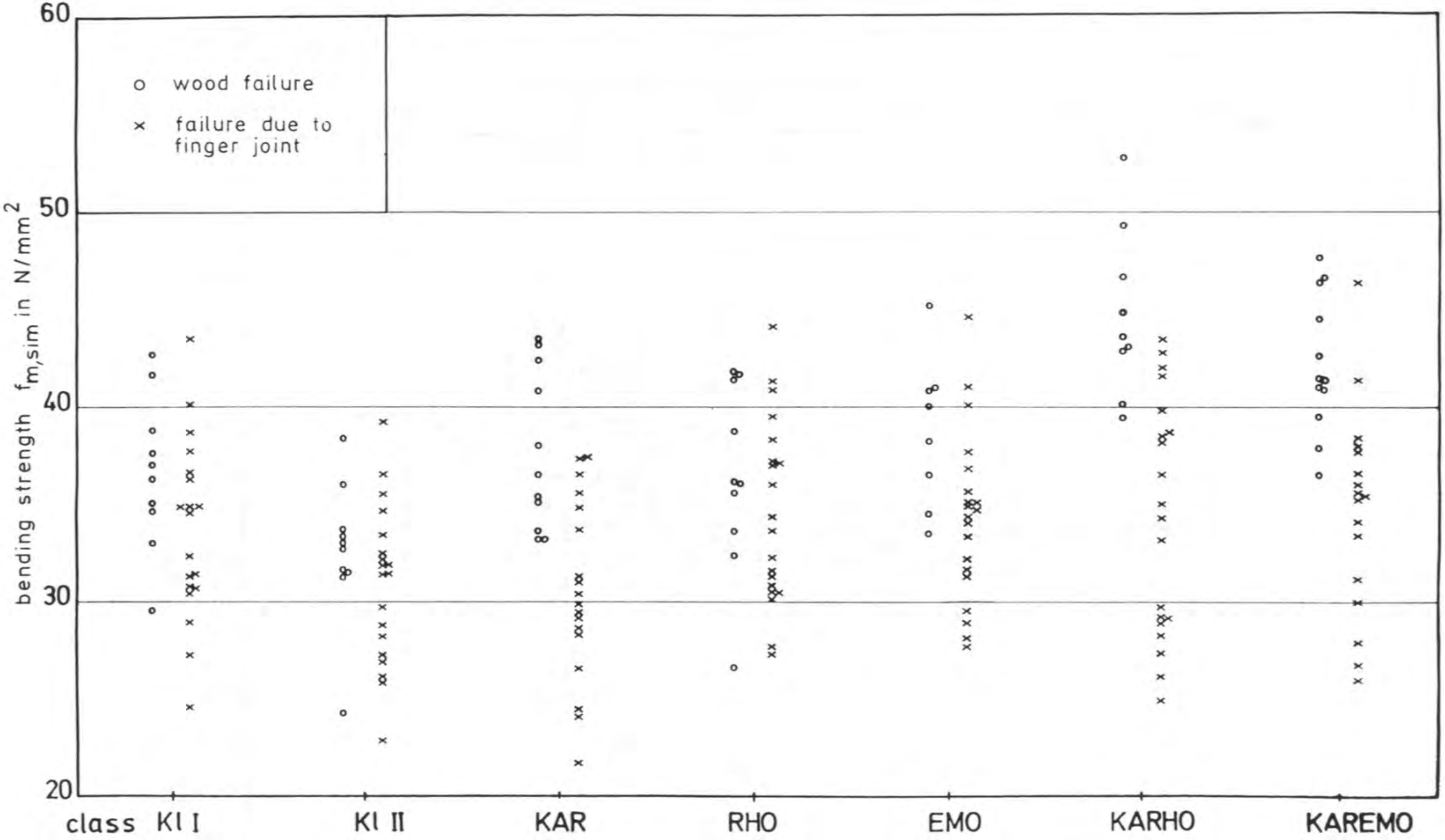


Fig. 9: Calculation results, series Ⓐ

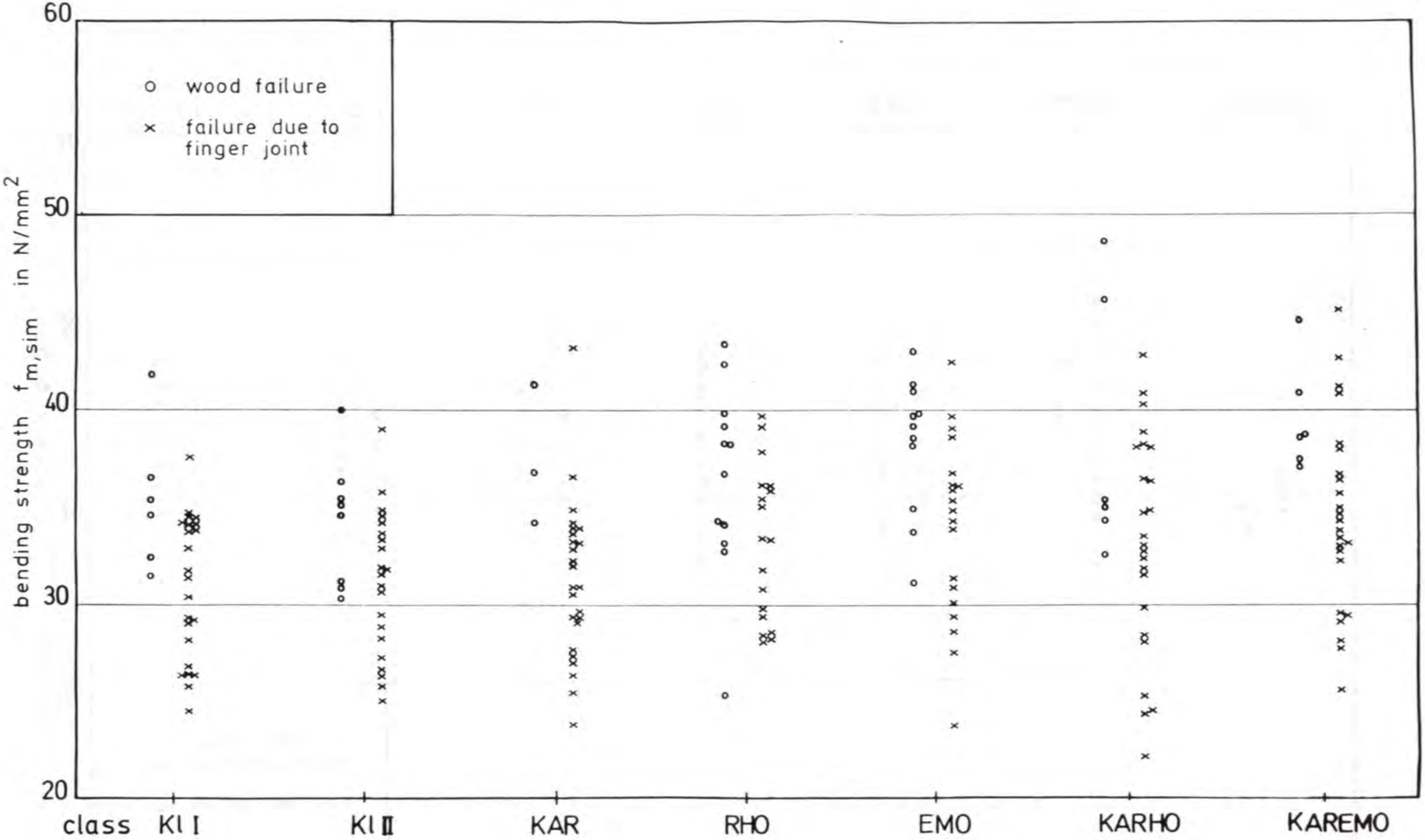


Fig. 10: Calculation results, series Ⓑ

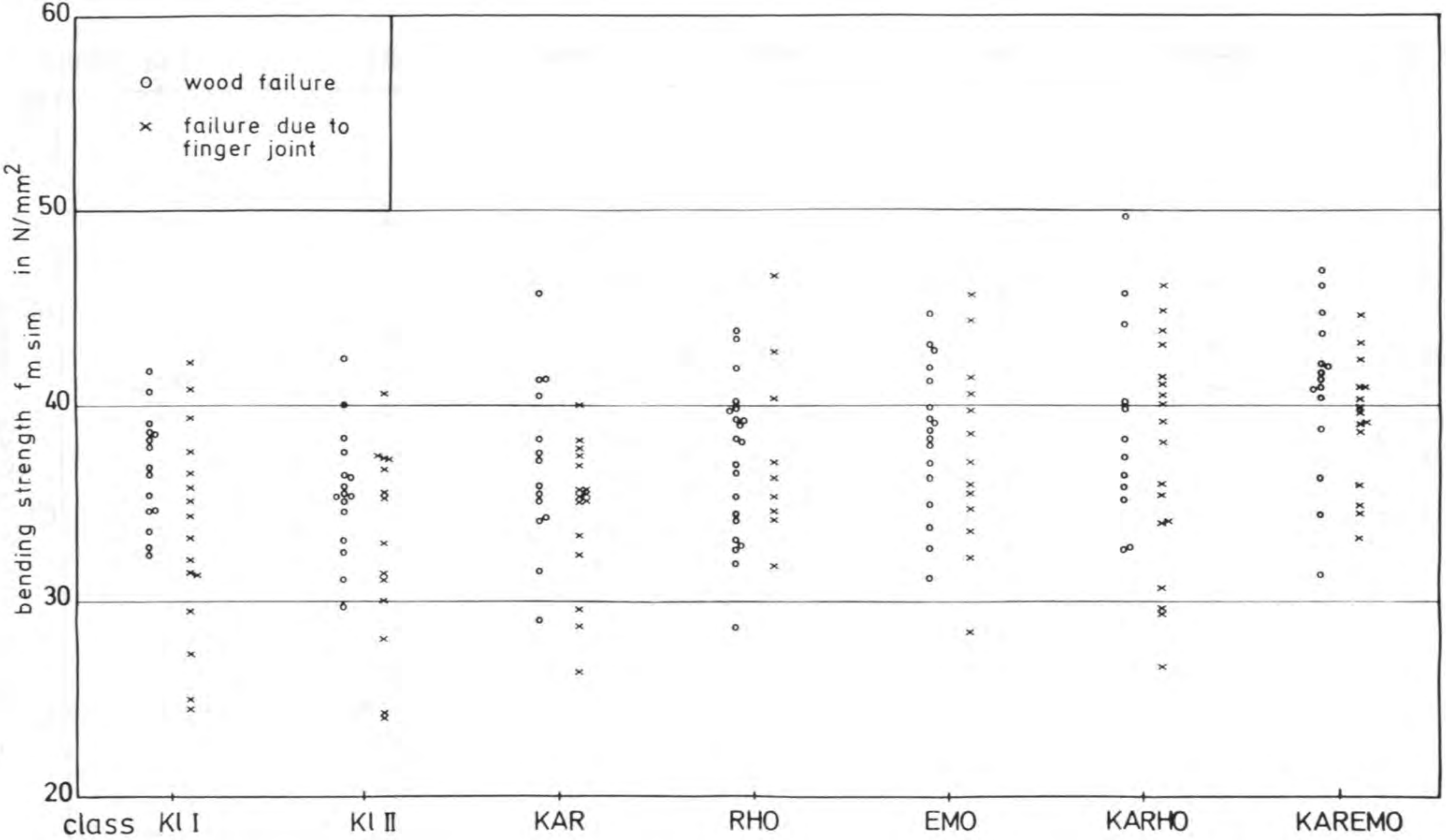


Fig. 11: Calculation results, series Ⓒ

Table 1: Regression equations for the determination of the MOE (in N/mm^2)

(valid for board sections with a length of 150mm approximately)

	regression equations	residue	coefficient of correlation
compression	$\ln (E_c) = 8{,}22 + 2{,}994 \cdot \rho_o - 0{,}76 \cdot KAR$	0,142	0,80
	$\ln (E_{c,fj}) = 8{,}282 + 2{,}53 \cdot \rho_{o,min}$	0,231	0,56
tension	$\ln (E_t) = 8{,}20 + 3{,}13 \cdot \rho_o - 1{,}17 \cdot KAR$	0,180	0,77
	$\ln (E_{t,fj}) = 8{,}459 + 2{,}517 \cdot \rho_{o,min}$	0,142	0,61

ρ_o = ovendry density [g/cm^3]

$\rho_{o,min}$ = lower value of the jointed boards

KAR = total KAR - value according to [7]

fj = finger joint

Table 2: Regression equations for the determination of the strength (in N/mm^2)

(valid for board sections with a length of 150mm approximately)

	regression equations	residue	coefficient of correlation
compression	$\ln(f_c) = 2{,}586 + 2{,}80 \cdot \rho_o - 0{,}825 \cdot \text{KAR}$	0,088	0,94
	$\ln(f_{c,fj}) = -3{,}05 + 0{,}66 \cdot \ln(E_{c,fj}) + 0{,}985 \cdot \rho_{o,min}$	0,116	0,92
tension	$\ln(f_t) = -4{,}22 + \ln(E_t) \cdot (0{,}876 - 0{,}093 \cdot \text{KAR})$	0,187	0,86
	$\ln(f_{t,fj}) = 2{,}716 + 5{,}905 \cdot 10^{-5} \cdot E_{t,fj}$	0,231	0,52
	resp. $f_{t,fj} = 6{,}90 + 66{,}3 \cdot \rho_{o,min}$	7,880	0,36

ρ_o = ovendry density [g/cm^3]

$\rho_{o,min}$ = lower value of the jointed boards

KAR = total KAR - value according to [7]

fj = finger joint

Table 3: Test results

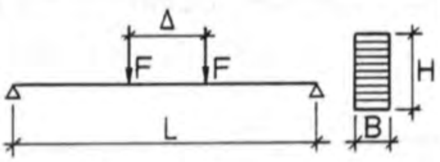
beam					bending strength	cause of failure
Nr.	L	Δ	B	H	f_m	
	mm	mm	mm	mm	N/mm^2	
I.1	3300	2000	100	250	39,9	knot
I.2					33,6	-"-
I.3					36,4	-"-
II.1	4650			500	35,3	-"-
II.2					38,5	-"-
II.3					29,9	-"-
III.1	7500			1000	28,9	-"-
III.2					30,0	finger joint
III.3					26,9	finger joint

Table 4: Requirements for the two outer tension laminations

grading	class	requirements		
		knots	ovendry density ρ_0 g/cm^3	MOE E N/mm^2
visual	Kl.I Kl.II KAR	Gkl.I[1] Gkl.II[1] KAR $\leq$ 0,10	- -	- -
machine	RHO EMO	Gkl.II[1] Gkl.II[1]	$\rho_0 \geq 0,50$ -	- E $\geq$ 15000
visual/ machine	KARHO KAREMO	KAR $\leq$ 0,10 KAR $\leq$ 0,10	$\rho_0 \geq 0,50$ -	- E $\geq$ 15000

1) according to [6]

Table 5: Calculation results; beams with wood failure

(series Ⓐ , Ⓑ and Ⓒ)

class	mean $\bar{x}$ N/mm^2	standard deviation s N/mm^2	coefficient of variation v %
Kl.I	36,4	3.3	9
Kl.II	34,4	3,5	10
KAR	37,3	4,0	11
RHO	36,7	4,4	12
EMO	38,4	3,6	9
KARHO	40,9	5,8	14
KAREMO	41,0	3,8	9

Table 6: Calculation results; beams with failure due to finger joints

class	mean $\bar{x}$ N/mm^2		standard deviation s N/mm^2		coefficient of variation v %	
	Ⓐ+Ⓑ	Ⓒ	Ⓐ+Ⓑ	Ⓒ	Ⓐ+Ⓑ	Ⓒ
Kl.I	32,1	33,5	4,3	5,3	13	16
Kl.II	31,0	33,0	3,8	5,1	12	15
KAR	30,9	34,5	4,2	3,8	14	11
RHO	33,9	37,6	4,4	4,7	13	13
EMO	34,0	37,5	4,8	4,8	14	13
KARHO	34,0	37,4	6,0	5,8	18	16
KAREMO	34,5	39,1	4,9	3,3	14	8