Strength of glued laminated beams

Tests of beams

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INSTITUTE OF BUILDING TECHNOLOGY AND STRUCTURAL ENGINEERING
AALBORG UNIVERSITETSCENTER · AUC · AALBORG · DANMARK

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PART 5

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NOTATIONS

Commonly used notations are given below. Notations used only locally are defined when used.

b	Width of beam with rectangular cross-section
c	Length of section with displayed axis, see fig. 4.2h
E	Modulus of elasticity
f	Strength
G	Shear modulus
h	Depth of beam with rectangular cross-section h_i thickness of lamina No. i
I	Moment of inertia/second moment of area
L	Beam span
ℓ	Moment arm
ℓ_1	Length of measuring bridge
M	Moment
t	Thickness
β	Factor
γ_{lam}	Lamination factor
ρ	Specific density
σ	Stress σ_0 stress at failure in outer tensile fibre σ_1 stress at failure in the middepth of laminae No. 1

Subscripts

c	Calculated
m	Bending
t	Tension
ult	Ultimate, at failure

I GENERAL

1. SUMMARY AND CONCLUSIONS

The purpose of this investigation has been to contribute to the setting up of a theory for the derivation of the strength and stiffness of glued laminated beams from the properties of the laminae. Especially, the influence of weak cross-sections in the laminae (e.g. finger joints) and the ratio between beam depth and laminae thickness have been investigated.

A survey of existing theories is given in chapter 2.

A total of 200 beams have been tested. 140 of these were ordinary glued laminated beams while 60 were container floor boards used as beams. The latter are treated in chapter 6 - 7.

The ordinary 140 beams had a depth of 220-230mm, a width of 100 - 140 mm and a length of about 4 m. In most of the beams the laminal thickness was 33 mm, but in one series the 4 outer tensile laminae were only 14 mm. 27 lay-ups were tested. They are described in chapter 3.

For the two outer tensile laminae different grades and qualities were used, some of them were finger-jointed either with ordinary finger joints or with specially weak finger joints. The latter were made by cutting off half of the finger length of one of the finger profiles, and a remarkable uniform strength was obtained.

The different qualities of laminae were tested in tension. The results are given in chapter 4. Apart from the tensile strength the lateral deflection of the laminae during axial tension was determined. The prevention of these deflections when the laminae are glued together is assumed to be one of the main reasons for the lamination effect, i.e. the fact that the bending strength of a beam is usually higher than the tensile strength of the laminae.

The main results of the tests of the ordinary beams are as follows:

- The bending stiffness could very accurately be calculated from the stiffness of the laminae.
- The shear modulus was independent of grade and lay-up, a value of G = 900 MPa and a ratio of $E_m/G = 14$ were found with a coefficient of variation of approximately 15 per cent.
- The failure mode depends on the lamina thickness and the depth of the beam. For relatively thick laminae the failure can be regarded as a number of successive failures: The failure starts in the outer tensile lamina, which is peeled off. The second lamina fails in the weakest section and is peeled off, etc. For thin laminae there is no peeling off and the failure is restricted to the vicinity of the initial failure.
- For the tested beams with 7 - 9 laminae the strength usually depended on the outer tensile lamina only, in some cases on the two outer ones. The rest of the laminae did not influence the ultimate strength although compression failures (wrinkles) were found, especially with high-quality tensile laminae.
- The exception from the general rule that the outer lamina only determined the beam strength was when the outer lamina was very weak. In this case the lamination factor was approximately 1 when number two lamina was also very weak. If number two lamina was of normal strength the lamination factor was approximately 1.4. The lamination factor is defined as the ratio between the failure stress of the beam and the tensile strength of the lamina.

- Laminae with ordinary finger joints had a lower strength than unjointed laminae of the same grade, but the strength of beams with finger joints was not impaired. The lamination factor for these beams was about 1.6.
- The beams with so thin laminae that peeling off did not occur had a lamination factor of about 1.7.
- For the rest of the beams the lamination factor was on average 1.4.
- Weak finger joints should be spaced at least 5 times the lamina thickness to avoid interaction.
- The container floor boards used as beams had unglued finger joints or finger joints made with very little end pressure. These beams had a very low strength, lower than would be expected even by disregarding one lamina.
- The strength value found from the tests for the lay-ups that correspond to the Danish commercial grade LT40 is lower than the value assumed in the code, the modulus of elasticity compare quite well.

2. INTRODUCTION

The basis for the design of glued laminated beams in the Nordic countries is the tests reported in [Moe, 1961]. 47 beams with different lay-ups and laminae grades and thicknesses were tested and lamination factors were determined as the ratios between the strength of the beams and the *assumed* tensile strength of solid wood of the same grade as the outer laminae.

Grade-dependent lamination factors as shown in table 2a were proposed. The grade of the outer tensile laminae is characterized by the short-term bending strength in kgf/cm^2, i.e. T300 has a bending strength of 300 kgf/cm^2 $\sim$ 30 MPa.

Table 2a. Lamination factors, γ_{lam}

Grade of outer tensile laminae	T390	T300	T210
γ_{lam}	1.2	1.3	1.4-1.5

The values of table 2a are still used in the Nordic timber codes even though production techniques have changed, the introduction of finger joints being the most important (the test beams were unjointed and in the production at that time scarf joints were used).

In the Anglo-Saxon countries the I_K/I_G-method has been used since the mid 1950's. The method was originally proposed in [Freas & Selbo, 1954] and has been elaborated in among others [Curry, 1961] and extended to include beams with mixed species and grades: [Bohannan & Moody, 1973], [Moody, 1974] and [Moody, 1977].

According to this method the lamination factor is given as a function of the ratio I_K/I_G, where I_G is the moment of inertia (second moment of area) of the gross section and I_K is the moment of inertia of the knot areas within a 1-foot long section. The method has proved satisfactory for assigning design strengths to the grades commonly used in USA and Canada, but its general validity has been doubted. Tests reported in [Madsen, 1962] and [Fox, 1978] did not support the theory, and studies of the effect of improving the quality of the outer tensile laminae by stricter grading rules - [Moody & Bohannan, 1970] - or by proof loading - [Strickler & Pellerin, 1974] - have revealed that it is possible to change drastically the beam strength without affecting I_K/I_G. The success of the I_K/I_G-method is probably due to a number of restrictions placed indirectly on the tensile laminae through the established grading rules and production procedures, restrictions that cannot generally be assumed, and especially not for European woods for which cutting and grading practices differ widely from those of North America.

In [Foschi & Barrett, 1980] a method for the simulation of the strength and stiffness of glued laminated members in bending and tension is set up. The laminae are divided into cells with a length of six inches (150 mm) and the method contains the following three steps:

1) To each cell is randomly assigned a knot size and a modulus of elasticity from known frequency data for the species and grades used. Similarly, a density is assigned at random to the entire lamina.

2) The stress distribution in each cell is calculated by a finite element method under the assumption of linear elastic properties.

3) In each of the cells with tensile stresses the maximum stress is compared to the estimated strength. The estimation is based on the following factors, among others:

- The statistical dependence of the tensile strength on knot size, modulus of elasticity and density.
- The influence of the stress distribution in the cell on the strength under the assumption of a brittle fracture theory corresponding to a 2-parameter Weibull distribution.
- The lamination effect, i.e. the support on a cell from the neighbouring cells reducing the bending stresses in the cell as compared to the conditions in a free tensile member.

The crucial part of the method is the failure criterion which is found by leaving open a number of parameters in the relations between strength and stiffness, etc. and then adjust them by comparing the theoretical results with test results of a number of beams. It is thus possible that the method is confined to the species, grades and sawing practice of the laminae of the tested beams.

The main purpose of the present investigations is to set up a failure criterion and especially to determine the influence of discrete weak sections (e.g. at finger joints and knots) and the influence of the laminal thickness in relation to the beam depth.

The test results of five series of beams are described and discussed. Series 1-4 were produced according to normal practice, except for the finger joints being in some cases of a specially low grade. They are described in part II. Series 5, where the test specimens were container floor boards usually used in flatwise bending, but in this case tested in edgewise bending is described separately in part III.

The beams are numbered X.YY.ZZ. X is the series number (1, 2, 3, 4 or 5). YY denotes the lay-up, see sections 3.1 - 3.4 and 6. ZZ is the number of a beam with a given lay-up.

The finger joints and the beams for series 1 - 4 were made by Limtræ Lilleheden A/S. Series 5 was made by Bullboard A/S.

II SERIES 1 - 4

3. TEST BEAMS AND TESTING

3.0 General

The laminae for series 1-4 were of Swedish whitewood (Picea Abies) graded according to the Nordic T-grade system in the following grades: T400, T300, T200, and Unclassified (Ucl.) corresponding approximately to the Standard Strength Classes SCL 38, SCL 30, SCL 24 and SCL 19 of [CIB, 1980]. The numbers of the T-grades indicate the magnitude of the bending strength in kgf/cm^2. The numbers of the CIB classes are the short-term bending strength in MPa. The T-grade system is described in e.g. [DS 413, 1974]. The properties of the laminae are further described in chapter 4.

Two types of finger joints were used. Ordinary finger joints - denoted F in the following - with a profile as shown in figure 3.0a, and specially made weak finger joints - denoted WF in the following. They were made by cutting off half of the finger length on one side, see figure 3.0b. The finger profile was visible on the wide face of the laminae (and not on the edges as the figures in sections 3.1 - 3.4 and 6 might indicate.

All boards used for the finger jointed laminae were 38 mm thick and of grade T400. Except for series 4 (see section 3.4) they were cut in the middle and cross-jointed as shown in figure 3.0c. One of the laminae was usually used for a beam while the other was tested in tension.

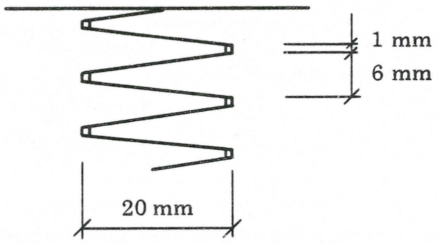


Figure 3.0a. Ordinary finger joints (F).

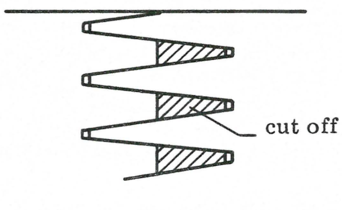


Figure 3.0b. Weak finger joints (WF).

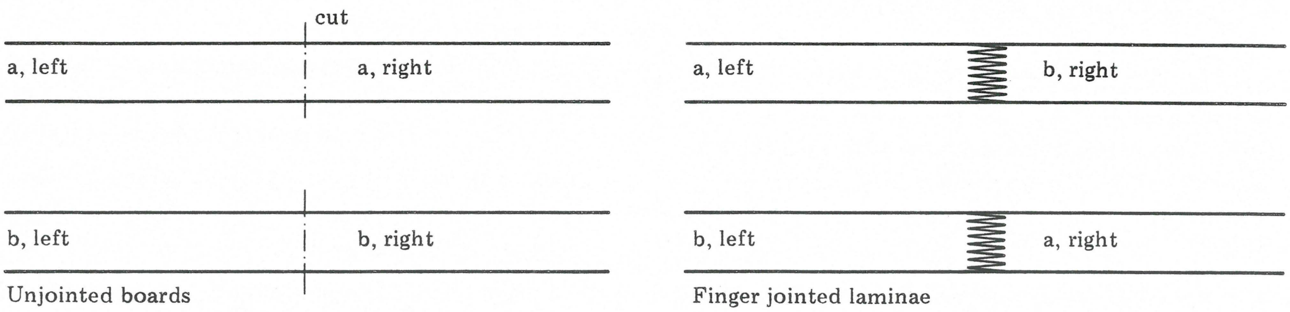


Figure 3.0c. Cross-jointing of laminae.

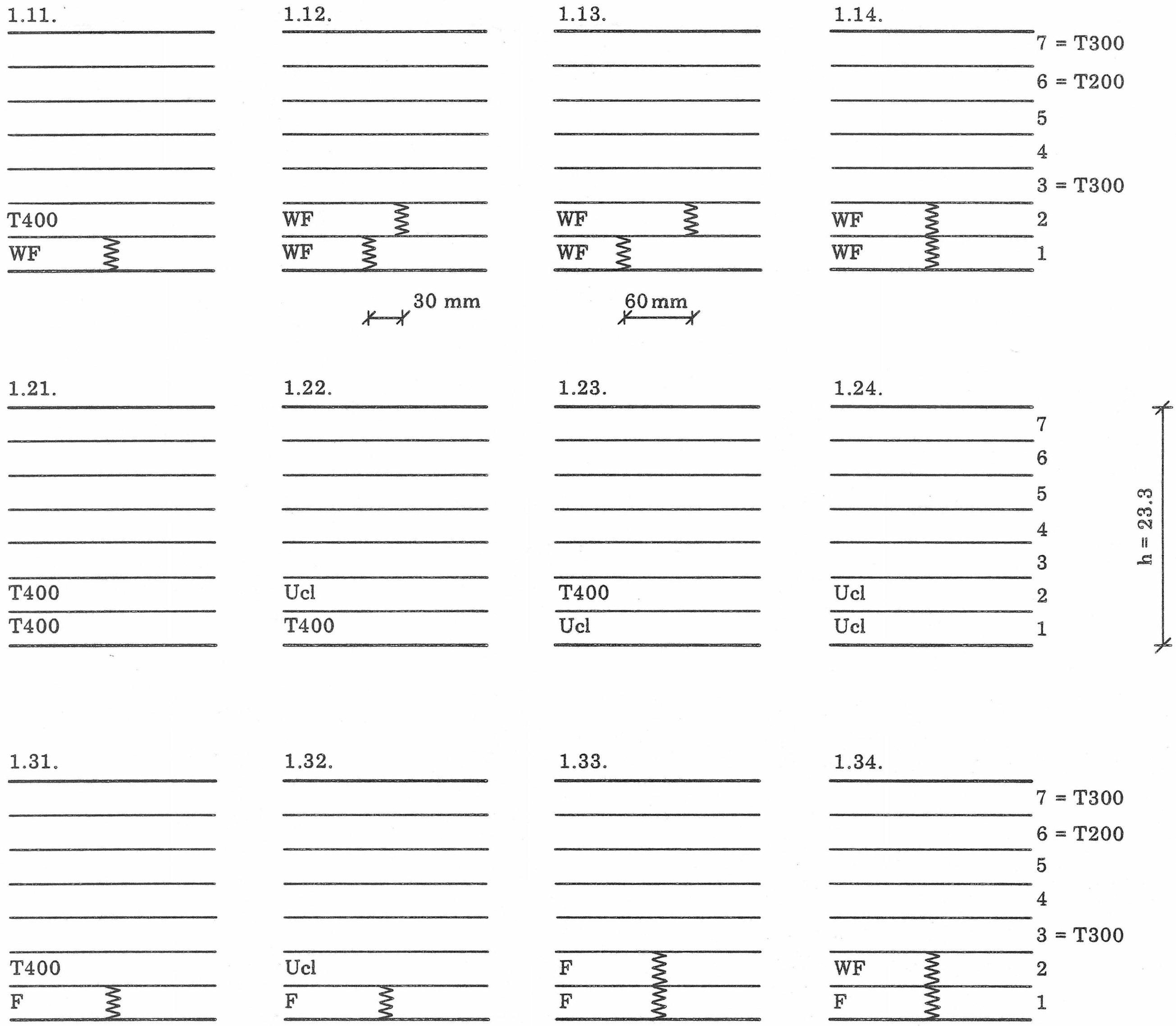


Figure 3.1 a. Lay-ups of beams series 1. Width b = 90 mm. F = finger joint. WF = weak finger joint.

All beams of series 1 - 4 had a length of approximately 4.0 m and a rectangular cross-section with width b and depth h. They were produced according to [DS 1118, 1980]. The glue was a resorcinol-phenol glue, cured at 40°C and at a clamping press of 0.6 MPa.

In the following the laminae are numbered 1, 2, . . ., from the tensile side.

3.1 Beams, series 1

The beams had seven laminae, each with a thickness of 33 mm (planed). The sawn width of the boards was 100 mm giving a width of the finished beams of b = 90 mm.

12 different lay-ups were tested, each with four replications, i.e. in total 48 beams. Figure 3.1 a gives the characteristics of the mid-length.

Laminae No. 3 and 7 were of T300, lamina No. 6 of T200. No special requirements were made for Nos. 4 and 5. The boards of a given grade were assigned at random to a beam or to a group used for the tensile testing, see section 4.

3.2 Beams, series 2

The beams had seven laminae, each with a thickness of 33 mm (planed). The sawn width of the boards was 150 mm, giving a width of the finished beams of b = 140 mm.

14 different lay-ups were tested, each with four replications, i.e. a total of 60 beams. Figure 3.2a gives the characteristics of the mid-length.

The finger-jointed laminae (WF) were of T400 with average modulus of elasticity (13600 - 15400 MPa). The boards with the highest modulus of elasticity, E, of the

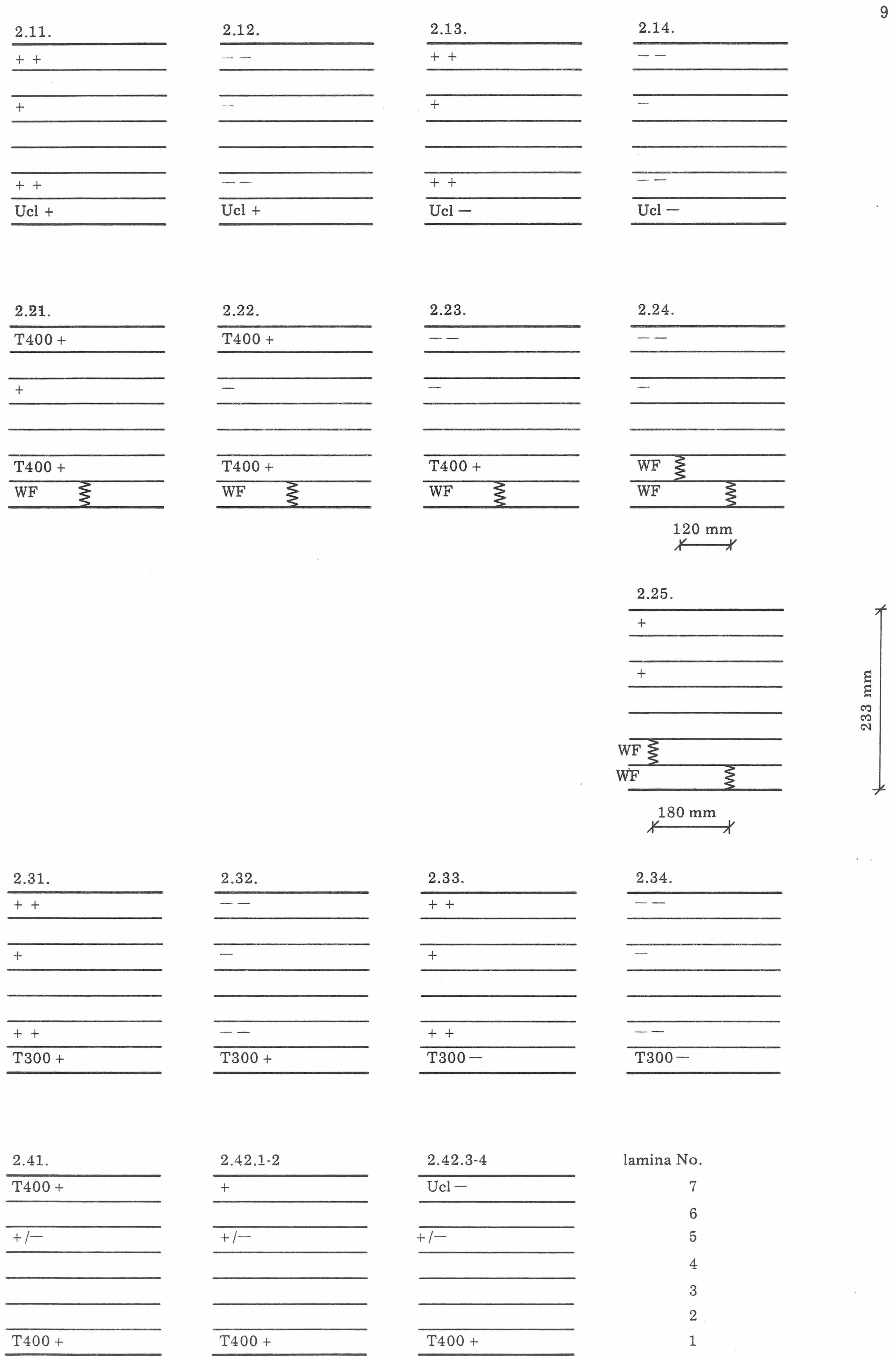


Figure 3.2a. Lay-up of beams, series 2. Width b = 140 mm. WF = weak finger joint. All laminae not especially marked are of the same quality as lamina No. 5.

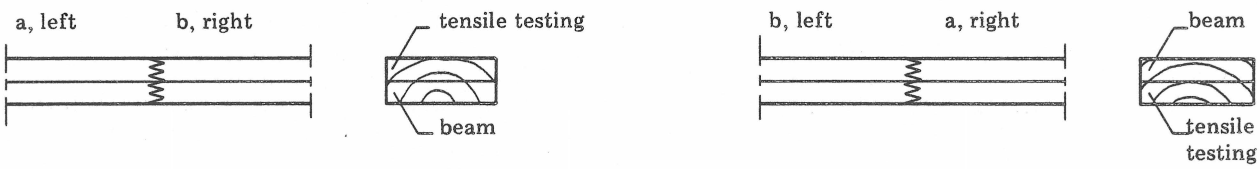


Figure 3.3 a. Use of split finger jointed boards.

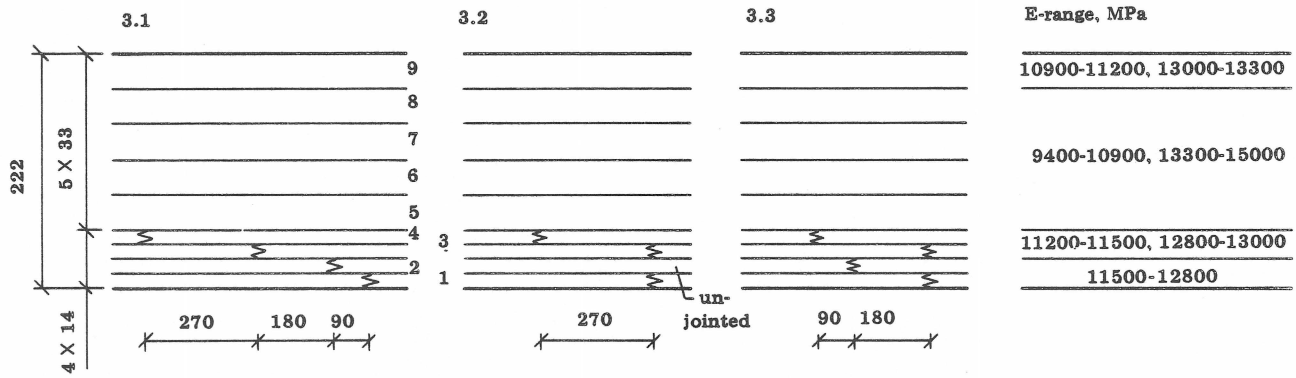


Figure 3.3 b. Lay-ups of beams, series 3. Width b = 90 mm. All finger joints are weak finger joints. Measurements in mm.

grade were used for the laminae denoted T400 + (16000 - 21300 MPa), T300 + (14900 - 19300 MPa), and Ucl + (14200 - 20100 MPa). Correspondingly, the boards with the lowest E-values of the grade were used for the laminae denoted T300 — (8500 - 10800 MPa) and Ucl — (8000 - 10000 MPa).

Having taken out the mentioned laminae together with corresponding boards for tensile testing the remaining boards were ranked independently of grade according to their modulus of elasticity. The boards with the highest E-values (> 15000 MPa) were used for the laminae marked with ++, those with the lowest E-values (< 10500 MPa) for the laminae marked ——. The remaining boards were divided into below average (10500 < E < 12000 MPa, marked —), average (marked +/—) and above average (13200 < E < 15000, marked +) and used for the ramaining laminae as indicated in figure 3.2a on lamina No. 5.

3.3 Beams, series 3

The beams had nine laminae, five with a thickness of 33 mm (planed) and four with a thickness of 14 mm. The sawn width of the boards was 100 mm giving a width of the finished beams of b = 90 mm.

The thin laminae were made by splitting the ordinary 38 mm boards. The finger-jointed laminae were initially cross-jointed as described in relation to figure 3.0c then split and used for beams and tensile specimens as shown in figure 3.3a.

Three different lay-ups were tested, each with four replications, i.e. a total of 12 beams. Figure 3.3b gives the characteristics of the mid-length.

All laminae were of grade T400. They were subsequently graded according to modulus of elasticity, E, and used as shown in figure 3.3b. Those with average E were used for laminae No. 1 and 2, those with near average E for laminae 3-4 and 9.

3.4 Beams, series 4

The beams had seven laminae, each with a thickness of 33 mm. The sawn width of the boards was 150 mm, giving a width of the finished beam of b = 140 mm.

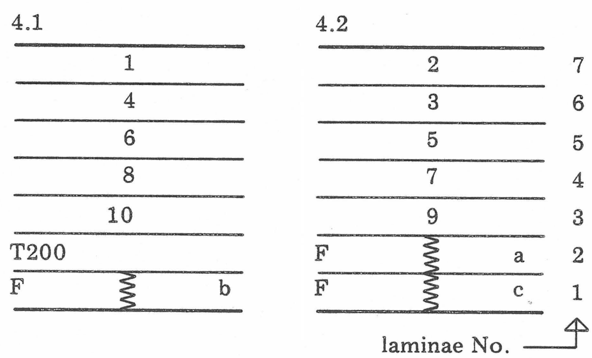


Figure 3.4 a. Lay-ups of beams, series 4, b = 140 mm. F = ordinary finger joints. The numbers on the beams are the rank of the laminae according to modulus of elasticity.

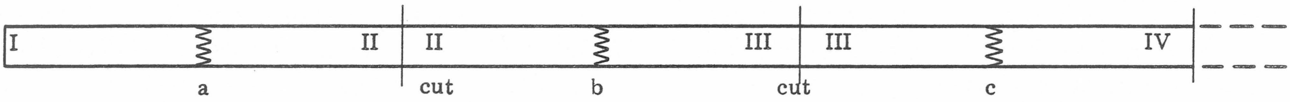


Figure 3.4b. The cutting of finger jointed laminae for a pair of beams. The three pieces a, b and c were used as shown in figure 3.4a.

Two different lay-ups were tested, each with ten replications, i.e. a total of 20 beams. Figure 3.4a gives the characteristics of the mid-length.

The finger-jointed laminae (of grade T400) and the T200 for lamina No. 2 were left-overs from the investigations of laminae for glued laminated beams described in [Larsen, 1978]. The finger joints for two matched beams (e.g. 4.1.1 and 4.2.1) were cut from a lamina as shown in figure 3.4b.

The rest of the laminae were of an average quality. They were ranked according to the modulus of elasticity, E (range 9900 - 17300 MPa). The ten with the highest E-values were used for beams 4.1.1 and 4.2.1 as shown in figure 3.4a. The next ten for beams 4.1.2 and 4.2.2 and so on.

The beams were tested as part of a master's thesis [Eriksen, 1979].

3.5 Testing of beams

The test set-up is shown in figure 3.5a and 3.5e. Details are shown in figure 3.5b - d.

The load was applied by a hydraulic jack with a built-in pressure cell. The reactions were taken by long bars allowing unrestrained longitudinal movements from the deformations of the beams. The load was transferred through steel plates and soft fibre board. The beams were laterally supported - spacing approximately 0.7 m - through steel wheels with roller bearings running on steel plates fixed to the sides of the beams.

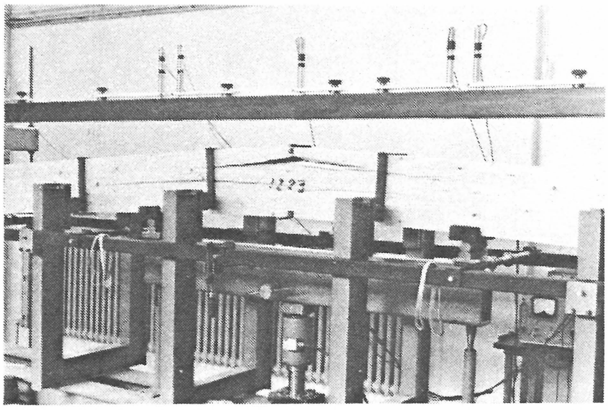


Figure 3.5b. Loading system.

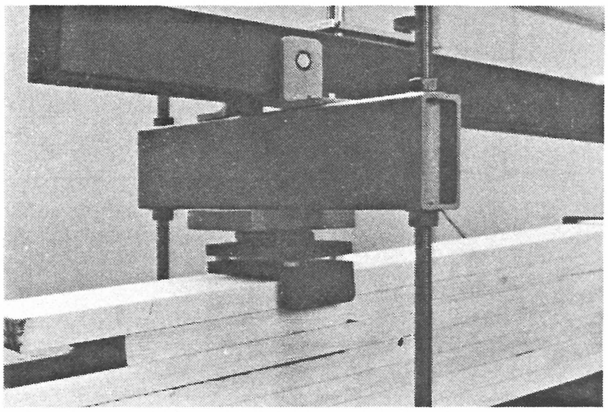


Figure 3.5c. End support.

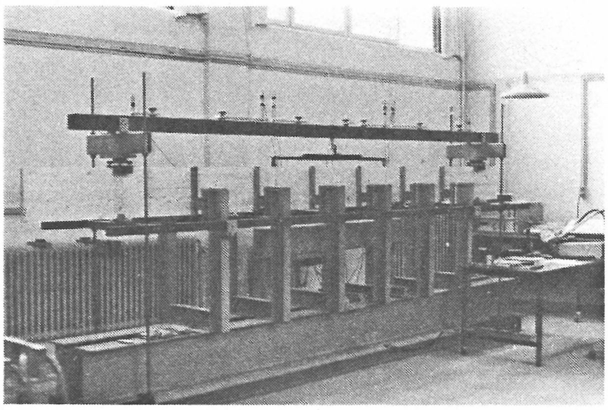


Figure 3.5a. Overall view.

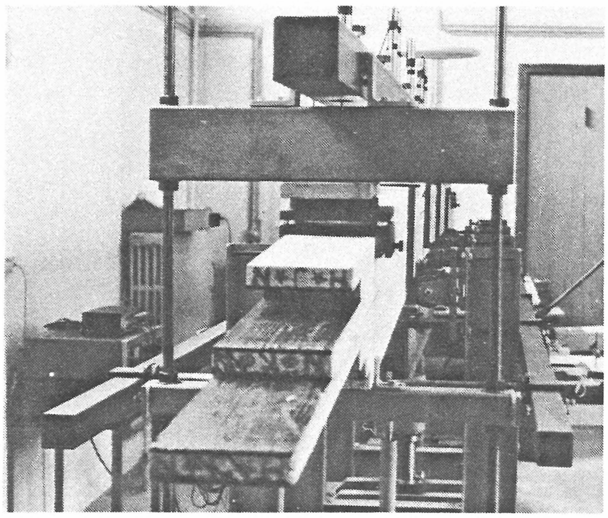


Figure 3.5d. Lateral support.

Three types of tests were performed for each beam except for series 4 where test type 1 was omitted. Reference is made to figure 3.5 e.

In test type 1 a three point (mid-point) loading and in test type 2 a four-point loading was used. The deflections were measured over the middle ℓ_1 = 1200 mm up to a load corresponding to a bending stress of about 8-10 MPa, i.e. well below the elastic limit.

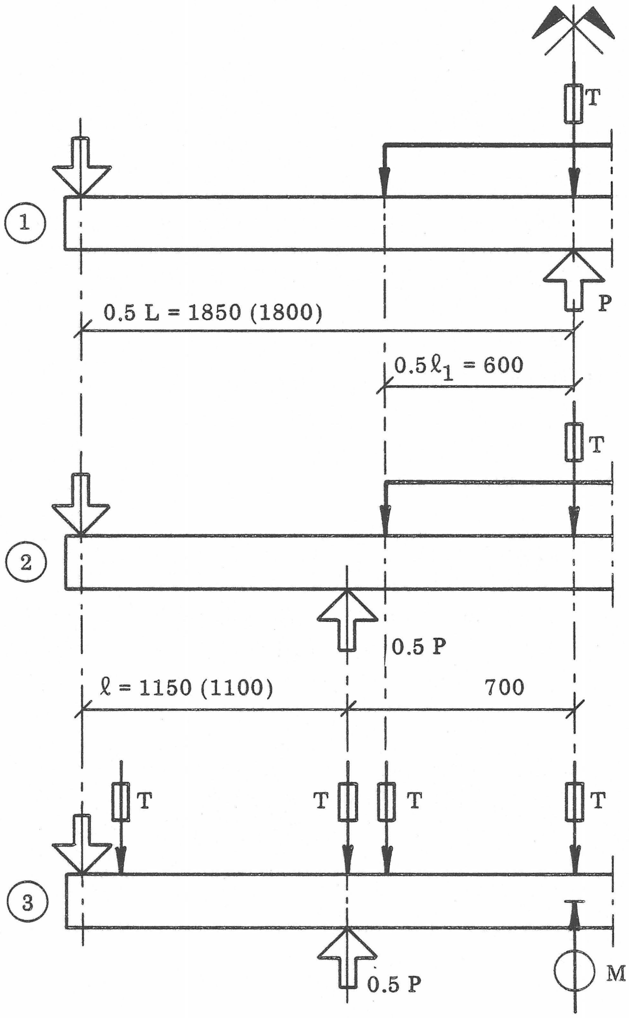


Figure 3.5 e. Test set-up. Measurements in mm. Measurements in ( ) are for series 4. T = deflection gauge (Transducer). M = Measuring clock.

In test type 3 the same four-point loading as in type 2 was used, the load was increased to failure. The time to failure was about 5-10 minutes. Up to about 2/3 of the ultimate load the deflections were measured with electric transducers in 7 points (in figure 3.5 e denoted T) and with an ordinary measuring clock (denoted M). For higher loads only M was used.

In some cases it was possible to reload the beams after an initial failure in one or more laminae, in som cases to a higher load.

4. LAMINAE

4.1 Measurements and tensile testing

For each board the following were measured:

- width, thickness and length,
- weight (not for series 3),
- moisture content (measured with a calibrated electric moisture meter),
- slope of grain (not for series 3),
- flatwise deflection over the middle 600 mm (series 4: 1200 mm) for a constant bending moment corresponding to a bending stress of about 10 MPa,
- knot pattern in 1 - 4 cross-sections at the middle 1200 mm (not for series 3).

The grade was determined according to the Nordic T-grade system. For series 1 the grade was also determined according to the ECE-system [ECE, 1977].

The specimens for tensile testing were tested in the testing machine described in [Andersen et al., 1977]. The free testing length was 2100 mm. The specimens were loaded in steps of approximately 2 MPa from 0 to 20

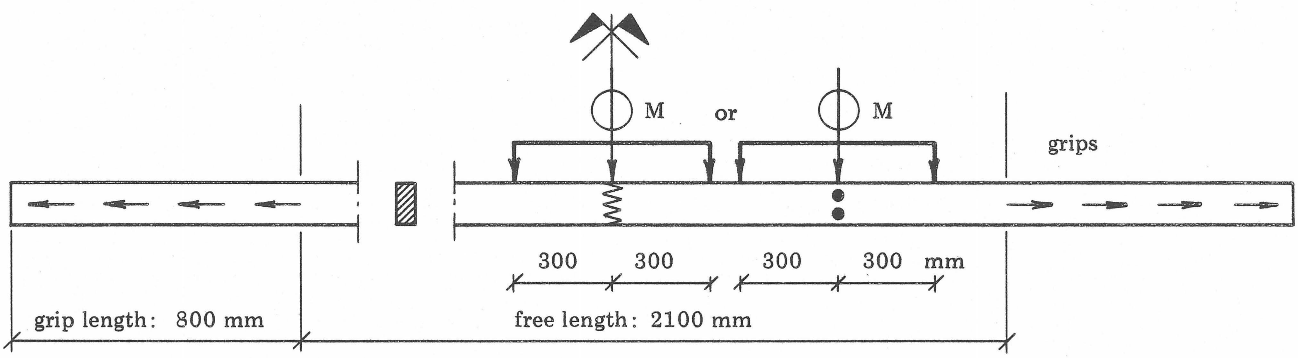


Figure 4.1 a. Tensile testing. The measuring clock (M) is placed over the finger joint at midspan or for the unjointed specimens over a grade-determining defect, if possible (i.e. not too near the grips).

MPa for the unjointed laminae and to 15 MPa for finger-jointed laminae, and the curvature corresponding to edgewise bending was determined by measuring the deflection over a length of 600 mm, see figure 4.1a. To avoid failure during measuring the finger-jointed specimens were initially proof loaded to about 16 MPa. Finally, the load was increased to failure which took place after a loading time of 3 - 5 minutes.

4.2 Test results

The moisture content was generally between 0.11 and 0.14 with a maximum of 0.16.

The dry weight was calculated and the specific density, ρ, determined based on dry weight and the directly measured dimensions. The modulus of elasticity, E, in bending was also calculated. The results are given in table 4.2a.

Table 4.2a. Modulus of elasticity in bending, and specific density. c.o.v. = coefficient of variation

		Modulus of elasticity, E, MPa			Specific density, ρ		
	No.	Mean	c.o.v.(pct.)	5-percentile	Mean	c.o.v. (pct.)	5-percentile
Series 1							
38 X 100	373	12550	16	9250	0.441	9	0.36
T400	143	13650	14	10200	0.450	10	0.38
T300	130	12150	15	9300	0.438	9	0.35
T200	75	11550	14	8700	0.436	9	0.36
Ucl	25	10900	16	8300	0.426	7	0.36
Series 2							
38 X 150	489	13050	19	9500	0.438	9	0.38
T400	177	14450	16	10400	0.450	9	0.38
T300	90	12750	18	9100	0.429	9	0.37
T200	109	11950	16	9000	0.426	7	0.38
Ucl	113	12200	17	9300	0.437	8	0.38
Series 3							
38 X 100	120	12250	18				
Series 4							
38 X 150	100	12850	16		0.413	10	

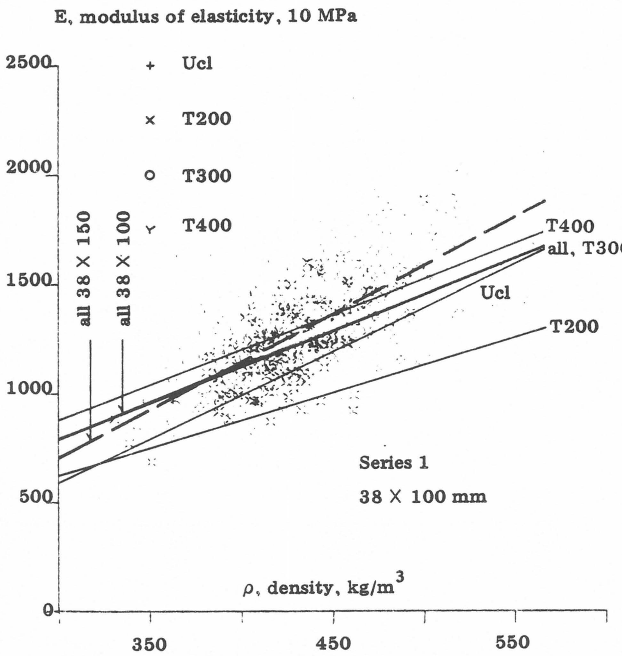


Figure 4.2b. E versus ρ for series 1. The regression lines are shown for the grades and for the total population. For comparison the regression line from figure 4.2c is also shown.

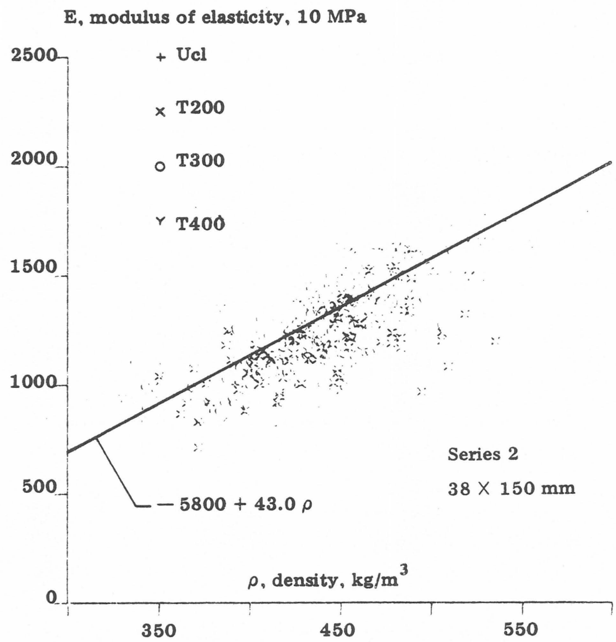


Figure 4.2c. E versus ρ for series 2. The regression line shown is for the total population.

Even though ρ for series 2 is less than for series 1, E is significantly higher for series 2. Disregarding T200/Ucl for series 2 the E-values for a given grade are significantly higher than for the lower grades.

The dependence of E on ρ is shown in figure 4.2 b and 4.2 c. The coefficient of correlation varied between 0.62 and 0.72.

Table 4.2d. Series 2. Number of boards according to the T-grading and the ECE-grading systems

ECE-grade	T-grade T400	T300	T200	Ucl	All
10	100	32	2	.	134
8	32	59	23	1	115
6	11	39	50	17	117
reject				7	7
	143	130	75	25	373

As mentioned the boards for series 1 were graded according to both the T-grade system and the ECE-system. The relations between the output for the two gradings are given in table 4.2d.

The ultimate stress in tension parallel to the grain - the tensile strength - is given in table 4.2e. The 5-percentiles - the characteristic values according to [CIB, 1980] - were determined by the method given in [Pierce, 1976] assuming a 3-parameter Weibull distribution.

The results for the unjointed laminae compare well with the results given in [Larsen, 1978] except for series 1, T200, which has an unusually low strength.

The separation of the unjointed laminae of series 2 into groups based on T-grade and modulus of elasticity is rather effective.

The strengths of the weak finger joints of series 1 and 2 (full thickness) are the same and approximately 60 pct of the corresponding unjointed laminae. The strength is very uniform, the coefficients of variation being only 15 - 19 pct.

Table 4.2e. Tensile strength f_t in MPa: Mean, coefficient of variation in pct, 5-percentile, and minimum value

		No. of speci-mens	Tensile strength f_t, MPa mean	c.o.v. (pct)	5-percentile	min
Series 1, 33 × 100						
Unjointed,	T400	23	39.2	33	18.6	17.0
	T200	7	23.8	16	14.9	17.6
	Ucl.	13	24.4	22	14.9	15.5
Jointed,	ordinary	20 (12)*)	27.4	25	17.6	17.9
	weak	24 (1)*)	23.8	15	16.6	16.7
Series 2, 33 × 150						
Unjointed,	T400+	8	52.6	16	42.1	43.2
	T300+	8	41.4	23	28.2	29.9
	T300−	8	24.7	16	19.3	19.9
	Ucl.+	6	31.7	20	19.2	22.8
	Ucl.−	8	21.3	18	13.0	15.0
	mean E	7	26.9	20	13.9	17.0
Jointed,	weak	20 (0)*	24.1	19	16.5	16.4
Series 3, 14 × 100						
Jointed,	weak	20 (2)*)	20.7	26	-	10.3
Series 4, 33 × 150						
Jointed,	ordinary	74 (6)*)	29.2	21	19.5	17.8

*) Numbers in ( ) are number of failures outside the finger areas. The strength of these were on average lower than for the finger failures.

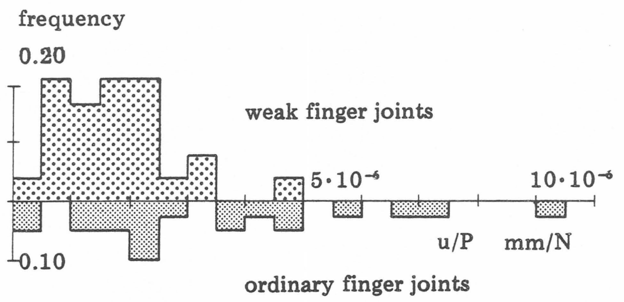


Figure 4.2f. Deflections of laminae, series 1.

The strength of the weak finger joints of series 3 (split from 38 to 14 mm) is significantly (level of significance < 0.005) lower than for series 1 and 2, and the variation is greater.

The deflections for series 1 and 2 during tensile testing were on average approximately 0 and in the following only the numerical values are discussed. Typical examples of the distribution are shown in figure 4.2f. The deflection is u for a load P.

No correlation between deflection and strength or stiffness of the individual specimens were found, and due to the high coefficient of variation (approximately 1.00) only the mean values Eu/P for the different groups are given in the first line of table 4.2g.

The grips of the testing machine are very heavy and stiff and the cross-sections just outside the grips are uniformly strained. For the rest of the specimens, however, the stresses are almost the same as for a specimen with hinged end conditions.

This can be demonstrated by the simple example shown in figure 4.2h: A tension specimen of length ℓ_t with built-in end is loaded by an axial force P. Over a length c at a distance x from the left end the elastic centre is displaced the distance y due to a defect, and the ordinary second moment of area I is reduced to βI.

A moment distribution as shown in figure 4.2h is found with the factors γ_1 and γ_2 given in table 4.2i.

With a free length of the specimen of about 2.0 m c/ℓ_t is probably less than 0.1 and the moment in the cross-sections with defects is reduced at most 16 per cent for a defect at midspan.

Due to the defect (the displaced axis) the specimen will deflect laterally under axial load. If the defect is placed at midspan the deflection measured over a length a placed symmetrically is u:

$$u = \frac{1.5\,Py}{\beta Ebt}\left(\left(1 - \frac{1}{\beta} - 1\right)\frac{c}{\ell_t}\right)\frac{c}{b}\left(2\frac{a}{b} - \frac{c}{b}\right) - \frac{c}{\ell_t}\left(\frac{a}{b}\right)^2\Big)$$

From this formula the y/b-values corresponding to the measured values of Eu/P are found. They are given in the middle section of table 4.2g for c/b-values of 0.5, 1 and 2. $\beta = 0.8$ has been assumed.

The maximum stress in the tensile specimen shown in figure 4.2h is

Table 4.2g. Results of deflection measurements

		Series 1, 100 mm					Series 2, 150 mm						All, mean
		Unjointed			Finger jointed		Unjointed					Jointed	
		T400	T200	Ucl.	Ordinary	Weak	T400+	T300+	T300−	Ucl +	Ucl −	Weak	
Eu/P	mm^{-1}	0.033	0.013	0.052	0.044	0.022	0.011	0.021	0.027	0.048	0.039	0.019	
y/b													
c/b =	0.5	0.11	0.042	0.17	0.14	0.071	0.57	0.11	0.14	0.25	0.20	0.098	
	1	0.056	0.022	0.089	0.075	0.038	0.31	0.059	0.076	0.14	0.11	0.054	
	2	0.032	0.012	0.050	0.042	0.021	0.019	0.036	0.046	0.082	0.067	0.032	
γ_{lam}													
c/b =	0.5	1.80	1.25	2.30	2.05	1.45	1.35	1.75	2.05	3.15	2.60	1.65	1.88
	1	1.35	1.10	1.55	1.45	1.20	1.20	1.35	1.50	2.00	1.75	1.35	1.40
	2	1.20	1.05	1.30	1.25	1.10	1.10	1.20	1.25	1.50	1.40	1.15	1.21

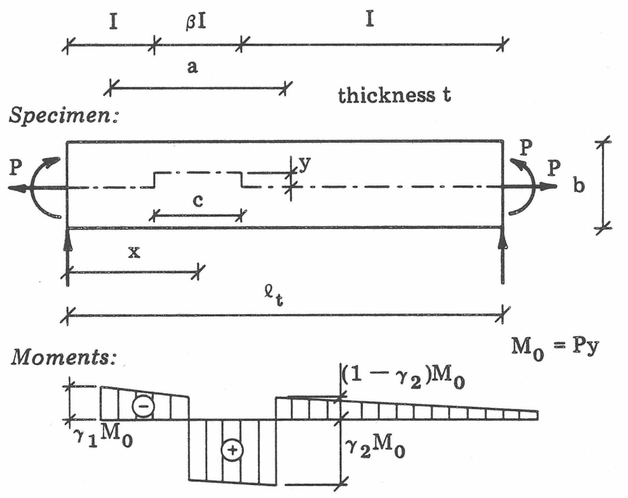


Figure 4.2h. Axially loaded test specimen with the elastic centre displaced y over the length c.

$$\sigma = \frac{P}{bt}\left(1 + 12\,\gamma_2 \frac{y}{b}\left(0.5 + \frac{y}{b}\right)\right)$$

If the lateral deflection was restrained - as is the case in a glued laminated beam - the maximum stress would be less. If it was held completely against lateral deflection the stresses would be uniformly distributed:

$$\sigma = \frac{P}{bt}$$

The lamination effect γ_{lam}, i.e. the ratio between the tensile strength of a lamina in a glulam beam and a free board can thus according to this primitive method be estimated at

$$\gamma_{lam} = 1 + 12\,\gamma_2 \frac{y}{b}\left(0.5 + \frac{y}{b}\right)$$

γ_{lam} is given in the bottom part of table 4.2g for each laminae type and quality together with the weighted mean.

Table 4.2i. Moment factors. γ_1 and γ_2

		$x/\ell_t = 0.25$		$x/\ell_t = 0.50$	
		c/ℓ_t		c/ℓ_t	
		0.05	0.10	0.05	0.10
$\beta = 0.8$	γ_1	0.15	0.30	0.06	0.12
	γ_2	0.89	0.81	0.94	0.88
$\beta = 0.6$	γ_1	0.20	0.37	0.08	0.16
	γ_2	0.87	0.76	0.92	0.84

The results vary rather much and not in a very systematic way, although for series 2 there is a trend of γ_{lam} increasing with decreasing grade.

5. BEAMS. TEST RESULTS AND DISCUSSION

5.1 Load-deformation relations

The load-deformation relations for tests type 1 and 2 were completely linear.

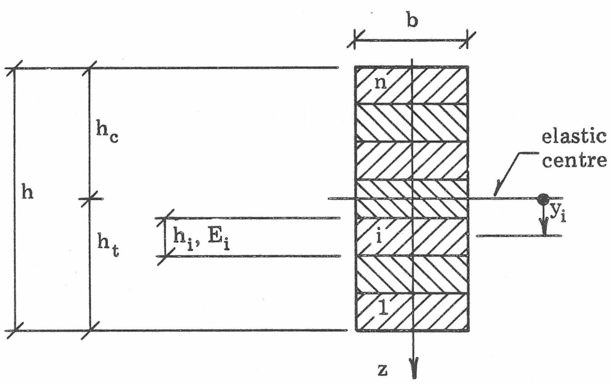


Figure 5.1a. Notations.

Table 5.1b. Measured and calculated values of E_m and G

Series No.	No. of tests	E_m mean MPa	$E_m/E_{m,cal}$ mean	$E_m/E_{m,cal}$ c.o.v. pct	G mean MPa	G c.o.v. pct	E_m/G mean	E_m/G c.o.v. pct
1	48	12400	1.008	5.4	909	11.9	13.7	10.0
2	60	12800	0.977	3.6	926	14.4	14.0	17.5
3	12	12300	1.012	4.7	924	15.1	13.5	15.4
4	20	12900	0.993	2.3	- - - - - - - - - - - - G is not determined - - - - - - - - - - - -			
			0.993		919		13.8	

The modulus of elasticity E_m in bending based on the deflections measured in four point loading was calculated for each beam as

$$E_m = 0.75 \frac{P}{u} \frac{\ell \ell_1^2}{bh^3} \qquad (5.01)$$

ℓ (the moment arm) and ℓ_1 (the length over which the deflections are measured) are defined in figure 3.5 e. u is the deflection for the load P.

For each beam the ratio $E_m/E_{m,cal}$ was determined. $E_{m,cal}$ is the modulus of elasticity in bending calculated from the measured modulus of elasticity for the individual laminae according to the theory of transformed sections.

The notations in figure 5.1 a are used.

The transformed elastic area is $(EA)_t$

$$(EA)_t = b \sum_{i=1}^{n} E_i h_i \qquad (5.02)$$

h_t is found from

$$0 = \sum_{i=1}^{n} y_i E_i h_i \qquad (5.03)$$

The transformed elastic second moment of area is $(EI)_t$

$$(EI)_t = b \sum_{i=1}^{n} (h_i^2/12 + y_i^2)\, E_i h_i \qquad (5.04)$$

and with $I = bh^3/12$

$$E_{m,cal} = (EI)_t/I \qquad (5.05)$$

The mean and coefficient of variation for each series of $E_{m,test}$ and $E_m/E_{m,cal}$ are given in table 5.1 b.

For mid-point loading (test type 1) the deflections over a length ℓ_1 at midspan due to bending is u_m

$$\frac{u_m}{P} = \frac{\ell_m^2 (3L - \ell_1)}{8E_m bh^3} \qquad (5.06)$$

L is the span, cf. figure 3.5 e.

The deflection u_v over the same length from shear (shear force $V = 0.5$ P) is

$$\frac{u_v}{P} = \frac{1.2\, \ell_1}{4Gbh} \qquad (5.07)$$

where G is the shear modulus.

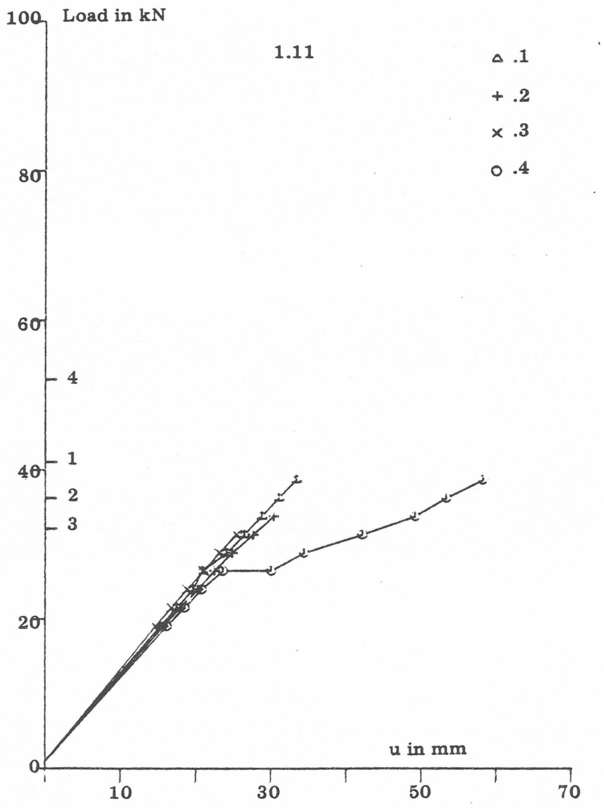
G can be found from the measured values u/P in test type 1 and the relation

$$u/P = u_m/P + u_v/P \qquad (5.08)$$

G and $E_{m,test}/G$ are also given in table 5.1b.

$E_m/E_{m,cal}$ is not significantly different from 1 for series 1, 3 and 4 (based on a level of significance of $\alpha < 0.10$).

For series 2, however, the deviation from 1.0 is highly significant ($\alpha < 0.00005$). A detailed investigation shows that it is due to a significant deviation from 1 for series



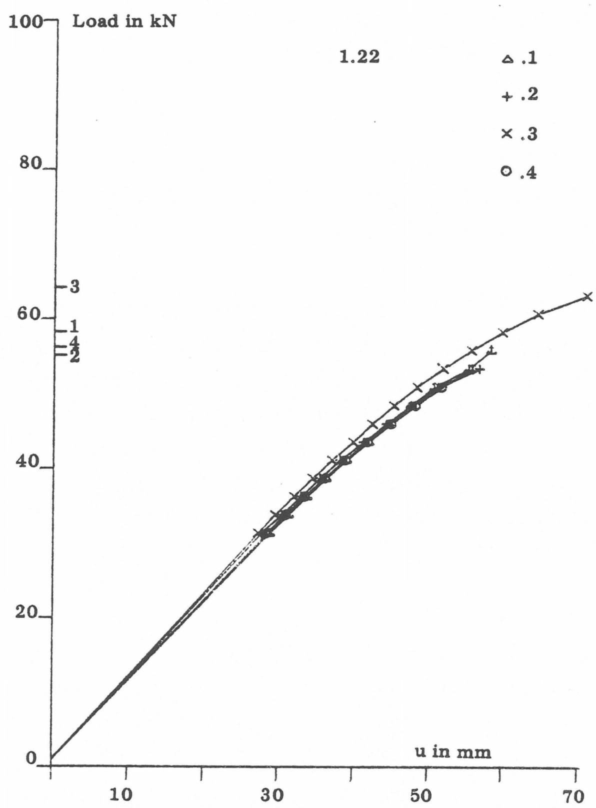


Figure 5.1c. Typical load-deflection diagrams. The abscissa is the mid-point deflection, the ordinate is the load, cf. fig. 3.5e. On the vertical axes the failure loads are shown for the four beams in a series.

2.2, i.e. beams with a weak finger joint in the outer tensile lamina. For the rest of the beams in series 2 the deviation from 1.0 is not significant.

No explanation of this deviation has been found.

There is no reason to suspect a local reduction of the laminal stiffness at the finger joint of the magnitude necessary to give a substantial reduction of the beam stiffness, and the reduction is not found in the other series with weak finger joints.

The G-values of the beams are the same for all series, and E/G are more variable than G. This is explained by the way the main variation of the beam stiffnesses is obtained, namely by selecting the outer laminae by their stiffness, while the inner laminae are of a more uniform quality.

Typical load-deflection diagrams for tests type 3 are shown in figure 5.1 c. Corresponding diagrams for all beams in series 1 - 4 are given in Appendix A.

The diagrams for series 1.11 are typical of beams with a weak finger joint. Three of the beams are linear elastic until failure, while beam 1.11.4 was linear elastic until an initial failure in the finger joints in the outer tension lamina at a load of 26 kN. Thereafter the remaining cross-section could be further loaded until ultimate failure at 52 kN.

The diagrams for series 1.22 are typical of beams with ordinary finger joints or unjointed laminae. The load-deflection relasionship is linear up to about 2/3 of the ultimate load. Above this load there is a moderate curvature.

5.2 Failure modes

All figures in this section show the beam as during testing, i.e. with the tensile side up (lamina No. 1).

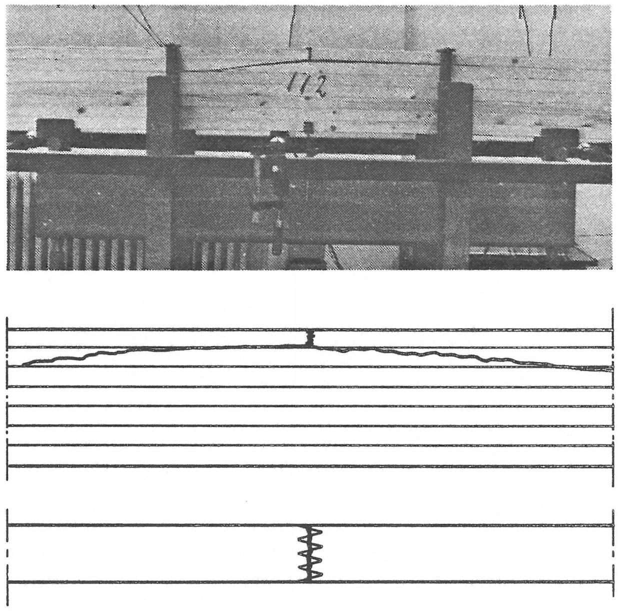


Figure 5.2a. Failure mode F1.

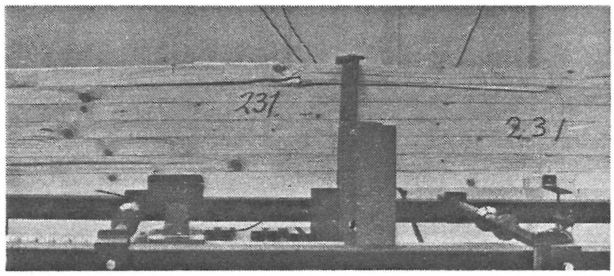


Figure 5.2b. Failure mode W1.

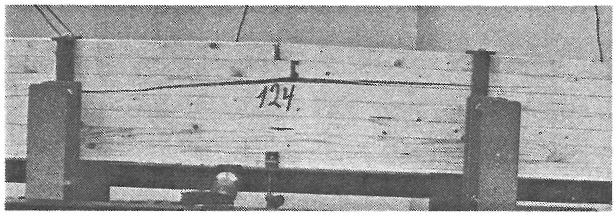


Figure 5.2c. Failure mode F2.

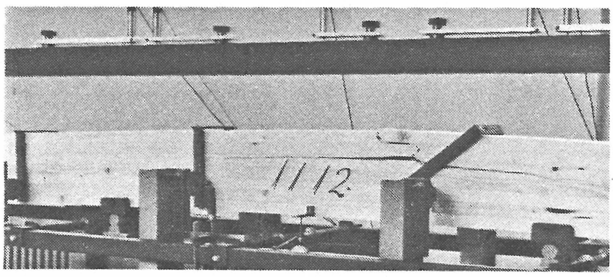


Figure 5.2d. Failure mode W2.

Failure mode F1

This is the typical failure mode for beams with one finger joint, especially a weak one. The failure starts as a tension failure in the finger joint in lamina 1, which is peeled off by splitting in the first glue line or along the fibres in lamina 2, in a few cases also in No. 3. In some cases it was possible to increase the load further until a new failure took place (cf. the load-slip line for beam 1.11.4 in figure 5.1c).

Failure mode W1

This failure mode is in principle as F1, but the failure in lamina 1 starts in the wood at growth defects, usually edge knots.

Failure mode F2

This is the typical failure mode for beams with two weak finger joints in the same or adjacent cross-sections. Lamina 1 and 2 act as one unit, which is peeled off after tension failure in the two finger joints. If the finger joints are not in the same cross-section they are connected by a shear failure in the glue line.

Failure mode W2

This failure mode is in principle as F2, but the failures are in the wood at growth defects in adjacent cross-sections.

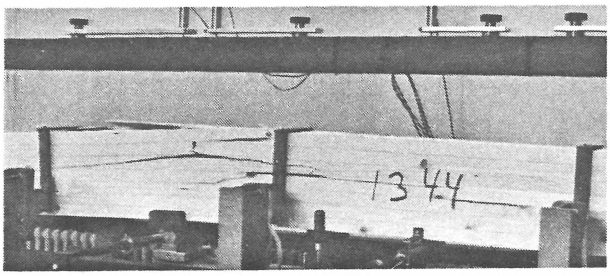


Figure 5.2e. Failure mode X.

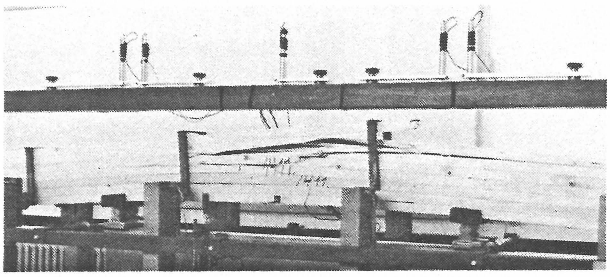


Figure 5.2f. Failure mode X.

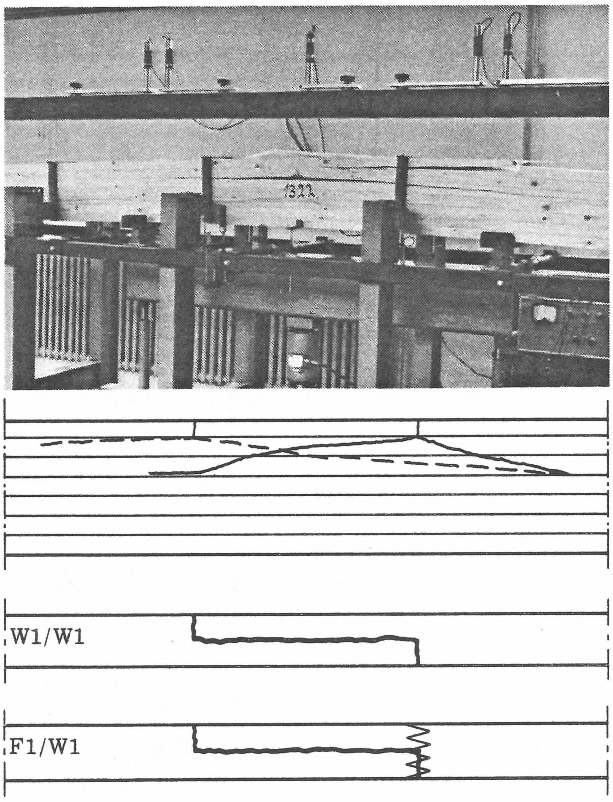


Figure 5.2g. Combined failures.

Failure mode X

The failure is running criss-cross through the beam with tension failures in the laminae (in finger joints or at growth defects) connected by shear failures in the glue lines or the wood. This failure mode could be the result of successive failures of type F1 or W1: The failure starts in lamina 1, which is peeled off, the remaining beam has insufficient strength, lamina 2 fails and is peeled off, etc.

Combined failure modes

The failure mode on the two faces of a beam were often different and even when the failure modes were the same, the failure patterns differed. The difference in failure patterns was made possible by longitudinal splitting visible on the wide faces of the laminae.

Compression failures

In a number of beams there were indications of compression failures (wrinkles) near ultimate load, especially for the beams in series 2 with strong tensile laminae. It is the impression, however, that compression failure was in no case the primary reason.

The failure modes for series 1, 2 and 4 are indicated in table 5.3 a. If the failure pattern were the same on both sides, only one failure mode is given, e.g. F1 or X. Where the failure patterns differed the failure modes of both sides are given as for example F1/F1, F1/X or X/X. If compression wrinkles were found a c is added.

It is notable that the failure mode was W2 in all cases with two weak finger joints in 33 mm laminae - i.e. the two finger joints interacted - irrespective of their

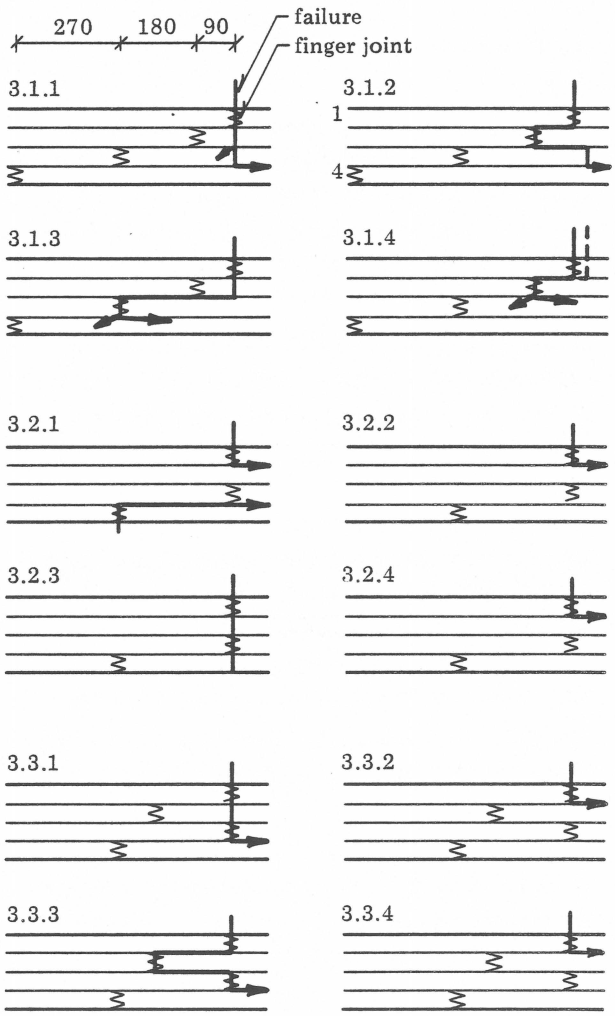


Figure 5.2h. Failures in beams, series 3. For beam 3.1.4 half of the failure in lamina 1 occurred through the finger joint, the other half through a knot.

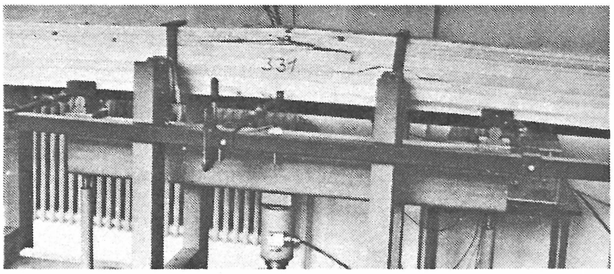


Figure 5.2i. Beam 3.3.1.

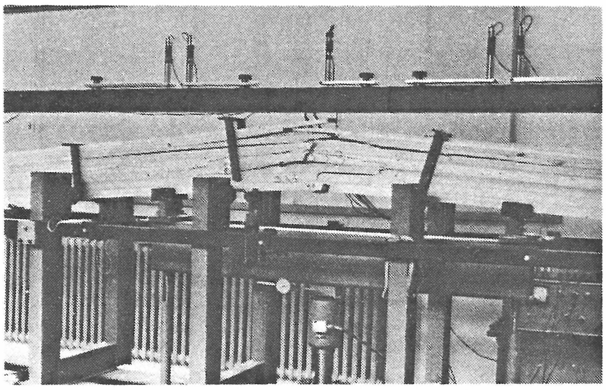


Figure 5.2j. Beam 3.3.3.

mutual distance (30 mm, 60 mm, 120 mm, and 180 mm).

For series 3 with the four thin tensile laminae the failure modes described above do not in all cases give an adequate description of the failures. Instead the failures are very schematically shown in figure 5.2 h. for the four thin laminae. Photos of typical failures are shown in figure 5.2 i - j.

In two cases in series 3.1 there was an interaction between the finger joints in lamina 1 and 2 (spaced 90 mm), but there was only one case of interaction of the finger joints in laminae 1 and 2 in series 3.3 (spaced 180 mm).

It was not possible to follow the development of the failure but for practically all the beams with 33 mm laminae (series 1, 2 and 4) the failure could as mentioned be regarded as successive failures and peeling offs of the laminae. In the case with two adjacent weak finger joints the two laminae acted as one lamina.

The difference between the beams with 33 mm and the beams with thin laminae (series 3) can be explained as follows.

If the outer lamina fails in tension a crack may develop as shown in figure 5.2 k. According to the theory of fracture mechanics for brittle materials this crack will be unstable, i.e. the laminae will peel off if

$$K \geqslant K_{crit} \qquad (5.09)$$

where K is the stress intensity factor which depends on

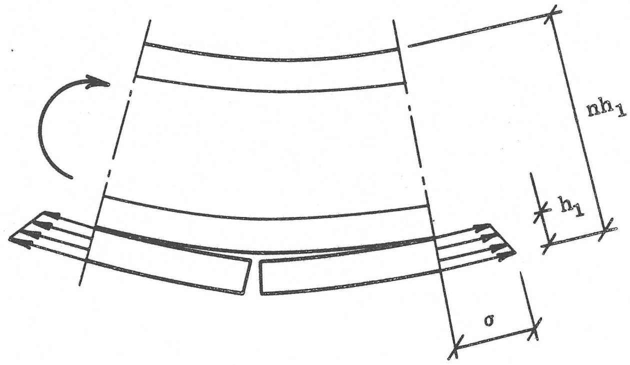


Figure 5.2k. Beam with n laminae each with a thickness of h_1.

Table 5.2ℓ. K/σ and σ_{crit}

n	h_1, mm	K/σ	σ_{crit}, MPa
7	33	0.53	19
3.5 1)	66 1)	2.5	4
16 2)	14	0.11	90

1) Corresponding to two 33 mm laminae acting in unison

2) Fictitious number corresponding to a beam depth of 222 mm, cf. figure 3.3 b (series 3)

the applied bending stress σ, the geometry (n and h_1) and the elastic properties.

K_{crit} is a material property called the critical stress intensity factor. According to [Smith & Penney, 1979] and [Byskov & Krenk, 1978] K_{crit} is about 10 $Nmm^{1.5}$.

As an approximation - [Smith & Penney, 1979] - K may be taken as

$$K = \frac{n^2}{(n-1)^2}\sqrt{\frac{n-1}{6((n-1)^3+1)}}\sqrt{h_1}\,\sigma \qquad (5.10)$$

In table 5.2ℓ K/σ and the critical value of σ, σ_{crit}, corresponding to $K = K_{crit} = 10$ $Nmm^{1.5}$ are given for the values of n and h of interest in this paper.

Since the stresses at failure are about 25-50 MPa it is explicable that peeling off is the ordinary for series 1, 2 and 4, but not for series 3.

5.3 Bending strength

The failure modes and stresses at failure in lamina 1 are given in table 5.3 a. It contains the following:

Column 1
The series number and lay-up, cf. figure 3.1 a, 3.2 a, 3.3 b, and 3.4 a.

Column 2
Number of beams of the type 1.

Table 5.3a. Failure mode and stresses at failure in lamina 1

1	2	3		4	5			6		7				8	9
Series No. and Lay-up	No. of beams	Quality of lamina No. 1	No. 2	Failure modes	Homogen. cross-section f_m mean		c.o.v.	Transformed cross-section σ_0 mean		σ_1 mean		c.o.v		σ_0/f_t	σ_1/f_t
					MPa		pct	MPa		MPa		pct			
1.11.	4	WF	T400	F1	31.6		22	34.0		28.9		27		1.43	1.22
.12.		WF	WF(30)	F2	25.6		20	28.3		24.2		20			
.13.		WF	WF(60)	F2	21.2	23.2	16	22.5	25.2	19.2	21.5	10	18	1.06	0.90
.14.		WF	WF(0)	F2	22.9		16	24.7		21.0		17			
1.21.		T400	T400	W1/W1(2) - W1/X(1) - W2/X(1)	45.7		13	49.2		41.9		22		1.25	1.07
.22.		T400	Ucl	X/X	45.0		7	50.1		42.9		10		1.28	1.10
.23.		Ucl	T400	W1(1) - W1/W1(1) - X/X(2)	40.6		14	34.0		29.1		6		1.39	1.20
.24.		Ucl	Ucl	W1/W1(1) - W2(2) - X/X(1)	33.3		13	28.7		24.7		4		1.18	1.02
1.31.		F	T400	F1	46.8		3	51.7		43.9		5		1.73	1.47
.32.		F	Ucl	F1/F2(1) - F2/X(2) - W2(1)	43.7		11	47.6		40.7		5		1.60	1.36
.33.	4	F	F(0)	F2/W2(1) - W1/W1 - W2/W2(2)	37.2		13	41.8		35.6		16		1.40	1.19
.34.	3	F	WF(0)	F2(2) - W2/W2(2)	39.0		5	42.1		35.9		10		1.41	1.21
2.11.	4	Ucl +	+ +	W1/W1C(2) - W1/W2C(2)	43.2		19	44.4		37.9		24		1.53	1.30
.12.		Ucl +	– –	W1/W1(1) - X/X(3)	42.6		7	52.7		44.7		7			
.13.		Ucl –	+ +	W1/W2C(1) - W2/W2(1) - X/X(2)	43.7		6	32.5		28.0		11		1.58	1.35
.14.		Ucl –	– –	W1/W1(1) - X/X(3)	36.4		12	34.6		29.6		13			
2.21.		WF	T400 +	F1	25.4		8	24.1		20.6		8			
.22.		WF	T400 +	F1C	30.3	29.1	19	28.8	29.3	24.6	24.9	20	16	1.22	1.03
.23.		WF	T400 +	F1	29.9		6	31.9		27.0		5			
.25.		WF	WF(80)	F2	31.0		13	32.2		27.5		14			
.24.		WF	WF(120)	F1/F2(1) - F2(3)	22.7		10	25.2		21.3		10		1.05	0.88
2.31.		T300 +	+ +	W1/W1C(3) - X/XC(1)	49.9		13	52.8	57.9	44.9	49.1	18		1.40	1.19
.32.		T300 +	– –	W1/W1	49.5		18	63.1		53.4		19			
.33.		T300 –	+ +	W1/W1(1) - W2/XC(1) - X/XC(2)	42.7		10	33.0	33.5	28.4	28.8	9		1.36	1.16
.34.		T300 –	– –	W1/W1C(3) - X/XC(1)	34.5		12	33.9		29.1		15			
2.41.	4	T400 +		W1/W1C(3) - W2/W2(1)	58.4		9	65.0		55.6		12			
.42.1-2	2	T400 +		X/XC	53.4		-	71.3	67.3	59.9	57.1		9	1.28	1.09
.3-4	2	T400 +		W1/W1(1) - X/XC(1)	54.1		-	67.9		57.5					
3.1.	4	WF	WF(90)		36.8		13	37.2		35.0		11			
.2.	4	WF	T400	See figure 5.2h	34.0		7	34.5	34.7	32.4	32.5	6	10	1.68	1.57
.3.	4	WF	WF(180)		31.7		3	32.3		30.2		7			
4.1.	10	F	T200	F1	45.0		18	45.7		39.2		17		1.57	1.34
.2.	10	F	F	F2	42.0		12	41.8		35.9		11		1.43	1.23

Column 3
Quality of the outer tensile laminae. The abbreviations are defined in 3.1 - 3.4. The numbers in brackets are the distances in mm between the two finger joints.

Column 4
Failure modes, cf. 5.2. If there were different failure modes the number of each type is given in brackets.

Column 5
The maximum bending stress at failure - the bending strength - if the cross-section was homogeneous

$$f_m = 6M_{ult}/(bh^2) \quad (5.11)$$

where M_{ult} is the bending moment at failure.

Column 6
The stress at failure (mean value of the beams with a given lay-up) in the outer fibre in tension taking into consideration the variable modulus of elasticity, see figure 5.1 a

$$\sigma_0 = E_1 M_{ult} h_t/(EI)_t \quad (5.12)$$

For beams with finger joints the stresses are calculated at either side of the joint and the larger value is given in the table.

Column 7
As σ_0 but in the mid-depth of lamina 1

$$\sigma_1 = \sigma_0(h_t - 0.5\,h_1)/h_t \quad (5.13)$$

Columns 8 and 9
The ratio between σ_0 or σ_1 and the mean tensile strength of the lamina f_t (the values given in table 4.2 e).

In some cases it was possible to reload the beam after failure in lamina 1. This was especially the case for the following lay-ups in series 2: 2.21, 2.22 and 2.23, and the results for these beams are given in table 5.3 b, where f_m is the bending strength for a 6 laminae deep homogeneous cross-section, and σ_0 and σ_2 are the stresses in the outside and the middle, respectively, of lamina 2.

In table 5.3 a the results for some of the series are pooled without statistical evaluation of the test results. This applies to the following lay-ups:

- *1.12 + 1.13 + 1.14:* There is no reason why the series with a spacing of 60 mm between WF (weak finger joints) should have a lower strength than the other two with spacings of 0 and 30 mm.
- *2.21 + 2.22 + 2.23 + 2.25:* There is no reason why 2.21 with unjointed inner laminae with high E-values should have a lower strength than the other ones (which are not different, statistically evaluated).
- *2.31 + 2.32:* There is no reason why 2.31 with high E of laminae 2 - 6 should have a lower strength than 2.32 with low E.
- *2.33 + 2.34:* There is no reason why σ_0 for 2.33 (high E) should be lower than for 2.34 (low E).
- *2.41 + 2.42:* There is no reason why 2.41 with T400 in lamina 7 should have a lower σ_0-value than 2.42 with a lower grade in lamina 7.
- *3.1 + 3.2 + 3.3:* There is no reason why 3.1 with a distance of 90 mm between the weak finger joints in lamina 1 and 2 should have a higher strength than series 3.2 (unjointed lamina 2) or 3.3 (distance 180 mm).

The statistical inferences are in the following estimated at a level of significance of $\alpha \leqslant 0.05$.

In general the strength depends only on lamina No. 1 and not on the other 6 laminae (8 in series 3), except for the influence of the E-variations on the stress distributions. It should especially be noted that there is no difference

Table 5.3b. Stresses at failure in lamina 2

1	2	3		5			6		7				8	9
Series No. and lay-up	No. of beams	Quality of lamina No. 2	No. 3	Homogeneous cross-section mean		c.o.v.	Transformed cross-section σ_0 mean		σ_2 mean		c.o.v.		σ_0/f_t	σ_2/f_t
				MPa		pct	MPa		MPa		pct			
2.21.	4	T400+	+	38.9	43.5	11	41.3	48.7	34.3	40.3	11	13	0.93	0.77
2.22.	4	T400+	–	49.6		7	52.7		43.8		7			
2.23.	4	T400+	– –	42.0		3	52.0		42.7		3			

in strength between 2.41 and 2.42 which have respectively a very stiff and a very weak laminae No. 7.

Exceptions from this general rule are some cases where lamina No. 1 is a weak one and lamina 2 is of the same or a lower quality. In these cases the strength depends on both laminae 1 and 2. This applies to series 1.11 + 1.12 + 1.13, 1.24, 1.33 + 1.34 and 2.24 if the evaluation is based on the ultimate strength (f_m).

By comparing 2.24 and 2.25 with 2.21 + 2.22 + 2.23 it is seen that in the beams with h_1 = 33 mm the finger joints in lamina 1 and 2 interact if they are spaced 120 mm (3.6 h_1) but that there is no strength reduction with a spacing of 180 mm (5.5 h_1) even though the failure pattern was W2 also in this case. From series 3 where h_1 = 14 mm it is found that the finger joints do not interact with a spacing of 90 mm (6.4 h_1).

The finger jointed beams - 1.31 + 1.32 - have the same strength as the corresponding beams - 1.21 + 1.22 - with unjointed lamina No. 1. The lower strength of the finger jointed laminae is thus not reflected in the beam strength.

The simplest failure criterions are of the form $\sigma_0/f_t = \gamma_{lam}$ or $\sigma_1/f_t = \gamma_{lam}$, where γ_{lam} are lamination factors depending on e.g. the grade of the laminae.

It is implicitely assumed that lamination factors should be greater than unity and since σ_0/f_t depends less on laminal thickness the form

$$\sigma_0/f_t = \gamma_{lam} \qquad (5.14)$$

is investigated. (σ_1/f_t is less than unity in some cases).

The mean value and the coefficient of variation for different types are given in table 5.3 c. The results from series 3 are significantly different from the corresponding specimens in series 1 and 2 and are therefore treated separately.

Table 5.3c.

Lamina No. 1	Lamina No. 2	No. of beams	σ_0/f_t mean	σ_0/f_t c.o.v. pct
Series 1 and 2				
Unjointed	Unjointed	44	1.39	16
F	Unjointed	18	1.61	12
F	F or WF	17	1.42	14
WF	WF	16	1.06	16
WF	Unjointed[1)]	20	1.26	26
Series 3				
WF	All	12	1.68	10

1) or WF spaced more than $5h_1$

Table 5.3d. Test values and code values for quality LT40

f_m and E_m in MPa	Test value f_m	Test value E_m	Code value f_m	Code value E_m
mean	43, 45	12300		14000
c.o.v., per cent	17	12		
5-percentile				
Weibull	30, 67	9800		
log-normal	32, 17	10050	40	12000

If the beams with weak finger joints in both lamina 1 and 2 are disregarded, there is a lamination effect of the same magnitude as calculated in table 4.2g with realistic c/b-values, viz. c/b equal to 0.5 - 1 for ordinary finger joints and c/b = 1 in other cases.

For beams with weak finger joints the value is much lower, the lamination factor being only slightly above 1.0.

The explanation can be that the conditions for the lamination effect is a certain plasticity so that stresses can be transferred from lamina 1 to lamina 2 around the weakest cross-sections of lamina 1. When a weak finger joint is glued to an ordinary lamina the latter can ensure the required plasticity, while this is not the case when two brittle areas (e.g. the weak finger joints) are glued together.

This could also explain why the lamination factor is higher when an ordinary finger joint is glued to an ordinary lamina, than when it is glued to another finger joint.

The higher values for series 3 can be explained by the difference in failure mode. In series 1 and 2 with the thick laminae, lamina No. 1 is peeled off and the failure can find the weakest section in lamina 2. In series 3 the failure is restricted to the vicinity of the failure section in lamina 1.

By reloading of the beams (table 5.3d) the lamination factor is slightly less than unity. The explanation for this low value can be that lamina 2 has been damaged during the preceding testing.

Generally, the lay-ups of the beams differ from the commercial lay-ups. The beams in series 1.31 - 1.33 and 2.31 - 2.34 correspond, however, rather closely to the Danish commercial quality LT40.

The values found by testing are given in table 5.3 d and compared with the values assumed in the Danish Timber Code [DS 413, 1982].

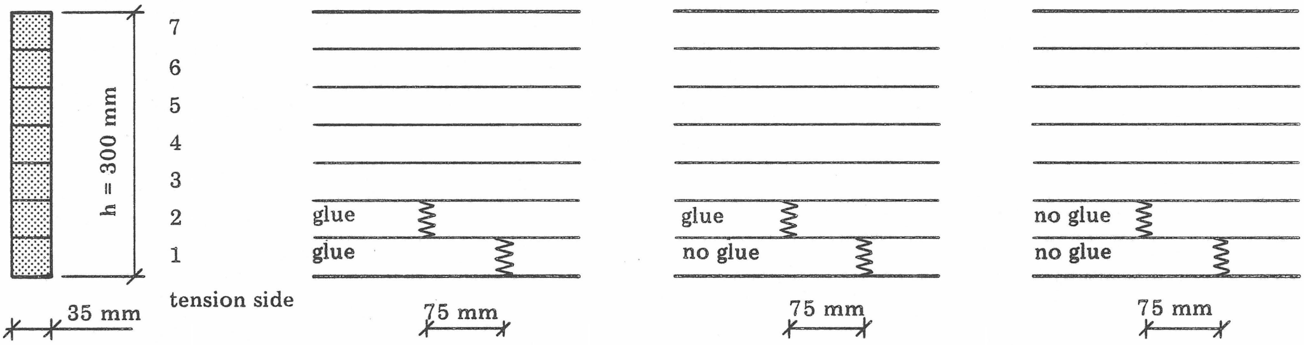


Figure 6.a. Lay-up of beam series 5. The fingers are a signature only, the finger profile is not visible on the faces of the beams but on the edges. Glue/no glue refers to the finger joints.

III SERIES 5

6. TEST MATERIALS AND TESTING

The beams in this series were container floor boards. They are normally used in flatwise bending, but in this case loaded edgewise as beams.

The beams (the floor boards) were made from 50 mm boards with a maximum length of 2.4 m. The boards were ripped and planed, fingers were cut at both ends, glue spread on the fingers and on the faces, and the beams then cured in a radio-frequency press giving only a small longitudinal force, if any, on the fingers.

The boards were unspecified Nordic softwoods with a mean specific density of 0.41 and a maximum knot size of 8 - 10 mm.

Three lay-ups were tested all with a cross-section as shown in figure 4.3 a and all with the minimum permitted distance - 75 mm - between a finger joint at midspan in lamina No. 1 and a finger joint in lamina No. 2.

Series 5.1 with 25 specimens corresponded to the normal production.

In series 5.2 - also with 25 specimens - there was no glue in the finger joint in lamina No. 1.

In series 5.3 with 10 specimens the glue was also omitted in the finger joint in lamina No. 2.

No testing was made of the individual laminae, but two series of »beams» with cross-sections 35 × 200 mm (5 laminae of 40 mm) were tested in tension. Series A (25 specimens) were from the ordinary production (i.e. they corresponded to beams series 5.1). In series B (25 specimens) glue was omitted in the finger joints in one of the face laminae (i.e. they corresponded to beams series 5.2). The specimens were loaded to failure without deflection measurements. The free test length was 1200 mm.

The beams were tested as described in 3.5 (figure 3.5 e) with the following adjustments:

- In series 5.2 the beams were initially loaded until a crack developed in the glue line at the unglued finger joint in lamina 1.
- The maximum stress in tests type 1 was approximately 5.5 MPa.
- In tests type 3 no deflection measurements were made.
- In series 5.3 tests type 1 were omitted.

7. TEST RESULTS AND DISCUSSION

7.1 Tensile strength

A typical tensile failure is shown in figure 7.1 a. Generally the failure passed all the finger joints on the free length, irrespective of their mutual distances, with shear failures in the glue lines connecting the joints.

The tensile strengths are given in table 7.1 b. The failure stresses correspond to the full cross-section, also in the case with an open finger joint in one of the face laminae. The failure stress calculated on a cross-section depth reduced by the depth of the face lamina can be found by multiplying by 1.25.

It is seen that there is no difference between the tensile strengths of the two specimen types.

The explanation is probably that the finger joints contribute very little to the strength as compared to the shear strength of the glue lines connecting the joints.

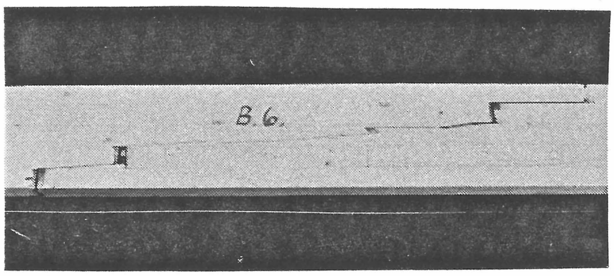


Figure 7.1 a. Tensile failure.

Table 7.1b. Tensile strength of 35 X 200 mm beams

Stresses in MPa calculated on full cross-section	Ordinary production	No glue in joints in face lamina
Number of specimens	25	25
Tensile strength, f_t, MPa		
mean	11.74	11.26
c.o.v., per cent	23	15
5-percentile, Weibull	8.2	7.9
5-percentile, log-normal	8.0	8.6
minimum	8.1	7.6

7.2 Modulus of elasticity

The modulus of elasticity in bending E_m and the shear modulus, G, is given in table 7.2. For the beams with an open finger joint (series 5.2) the values are calculated on a cross-section reduced by the depth of one lamina. Even then both E_m and G are reduced (the reduction would have been much greater if the total depth had been used).

7.3 Bending strength

A typical failure in bending is shown in figure 7.3 a.

Bending stresses at crack opening σ_{crack} in the glue line at the finger joints for series 5.2 and 5.3 and at failure are given in table 7.3 b. All stresses are calculated on the full cross-section. If instead a cross-section reduced by one lamina were used the stresses would be 35 per cent higher.

For series 5.1 two values are given. f_m corresponds to failure in lamina No. 1. $f_{m,ult}$ corresponds to complete failure. For the cases where complete failure was associated with failure in lamina No. 1 the same value is used for calculating the two mean values, etc.

Table 7.2. Modulus of elasticity in bending E_m and shear modulus G, in MPa

	Ordinary production	No glue in joints in face lamina
E_m		
mean	8550	7850
c.o.v., per cent	15	22
minimum	5510	4550
5-percentile, Weibull	5950	4850
5-percentile, log-normal	6500	5250
G		
mean	1130	1000
c.o.v., per cent	31	43

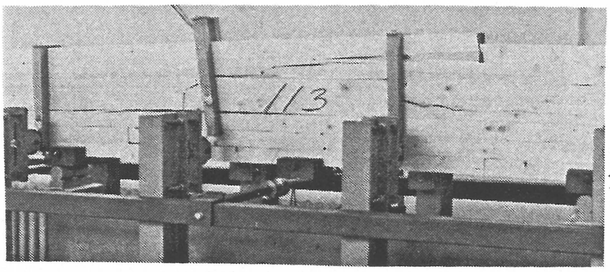


Figure 7.3a. Typical failure in bending.

For series 5.2 f'_m corresponds to failure in lamina No. 2 (failure in lamina 1 took place at σ_{crack}) and $f_{m,ult}$ to complete failure.

In series 5.3 failure in laminae 1 and 2 took place simultaneously at σ_{crack}, and $f_{m,ult}$ thus corresponds to failure in lamina 3 also.

The values of f_m and $f_{m,ult}$ for series 5.1 are statistically different from the other two series, which are not statistically different.

Table 7.3b. Crack stresses and failure stresses. Stresses in MPa.

	Series 5.1		Series 5.2			Series 5.3	
	f_m	$f_{m,ult}$	$\sigma_{crack}=f_m$	f'_m	$f_{m,ult}$	$\sigma_{crack}=f_m$	$f_{m,ult}$
mean	13.54	15.40	10.44	12.50 1)	10.75 1)	9.89	10.30 1)
c.o.v., per cent	21	18	19	21	18	13	18
minimum	9.92	9.92	7.61	8.59	7.61	8.12	8.12
5-percentile, Weibull	9.70	10.15	7.68	8.28	7.69	7.93	7.93
5-percentile, log-normal	9.41	11.03	7.51	8.59	7.86	7.95	7.78
f_m/f_t, f'_m/f_t, $f_{m,ult}/f_t$	1.15	1.31	0.93	1.11	0.96	0.88	0.92

All stresses are calculated on the full cross-section.

1) If the lamina 1 is disregarded $f_{m,ult}$ = 14.42 MPa for series 5.2 and $f_{m,ult}$ = 14.1 for series 5.3 is found

If the tensile strength is taken as the values given in table 7.1 b, i.e. f_t = 11.74 MPa for series 5.1 and 11.26 for series 5.2 and 5.3 (in lack of test results corresponding to series 5.3) ratios as shown in the last line of table 7.3 b are found. They correspond reasonably well to the values found for series 1-4.

For the density and grade a bending strength of at least 35 MPa would have been expected but it is only 15.4 MPa for series 5.1 and 14-15 MPa for series 5.2 and 5.3. The last values are found by using a cross-sectional depth reduced by the depth of the face lamina. It is thus not on the safe side just to disregard one lamina in beams with butt joints.

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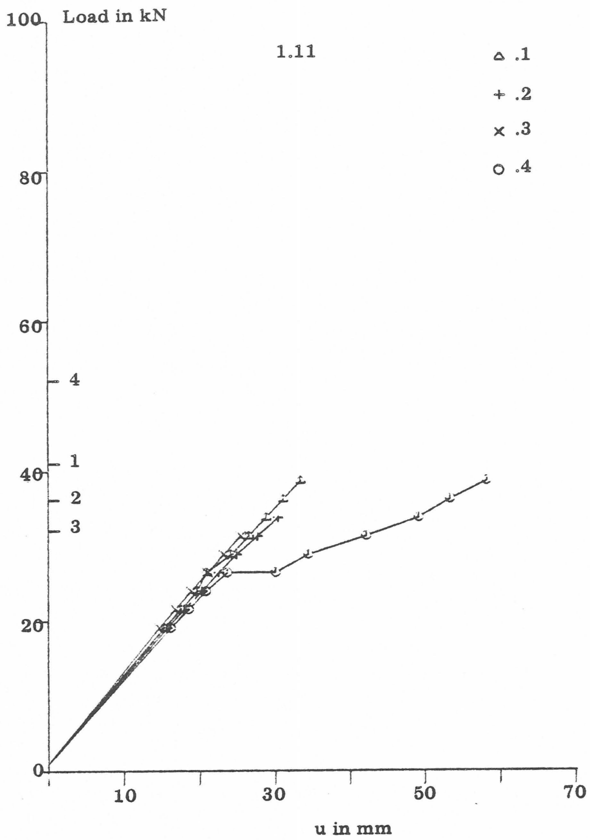
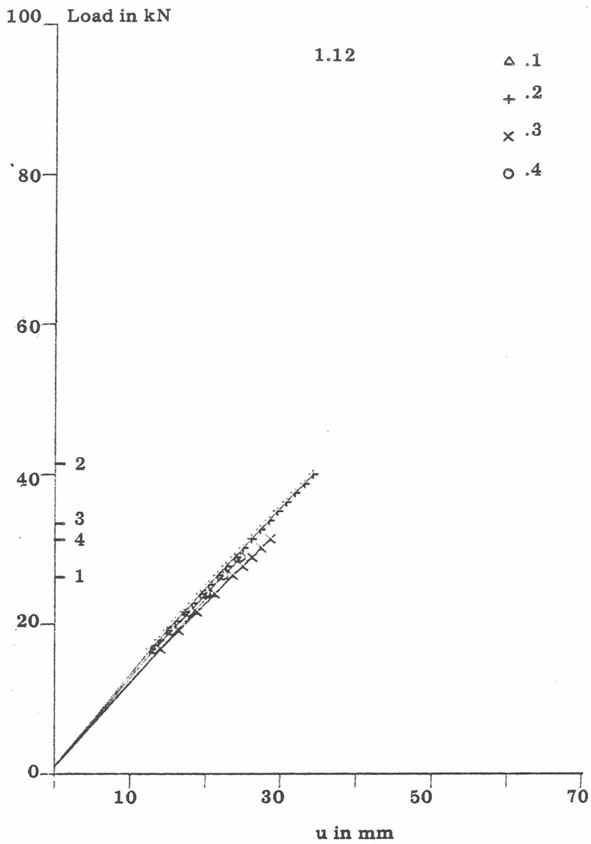
ANNEX A

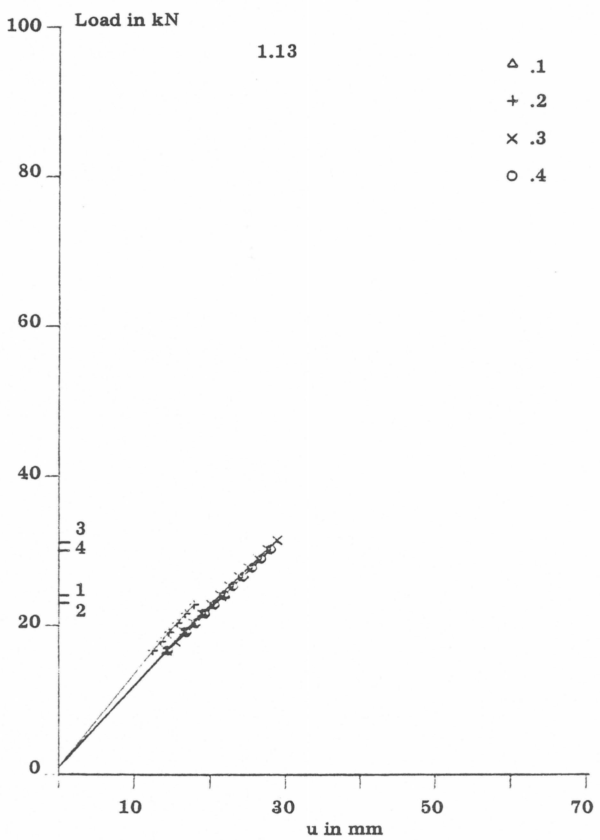
In the following load-slip curves for all beams in series 1 - 3 are given.

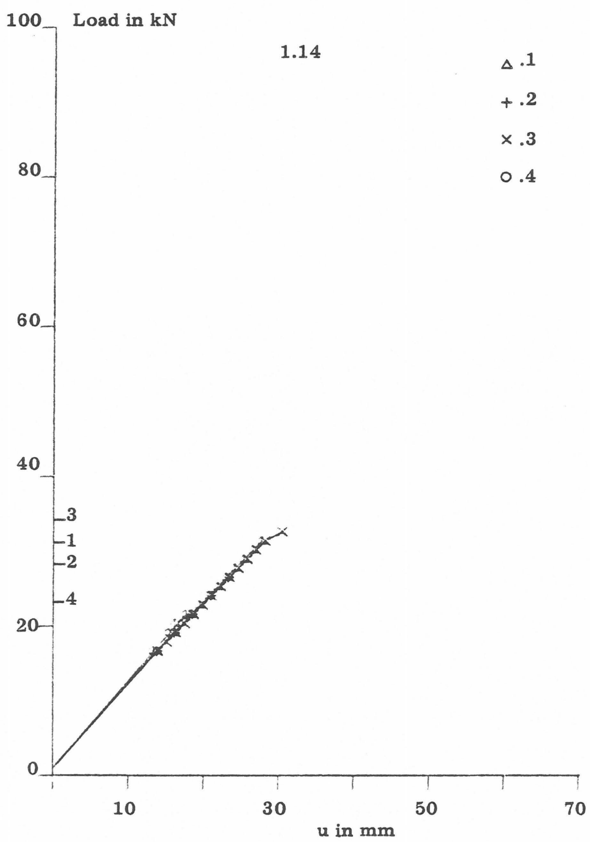
The ordinate is the total load in kN. On the ordinate the failure loads are marked.

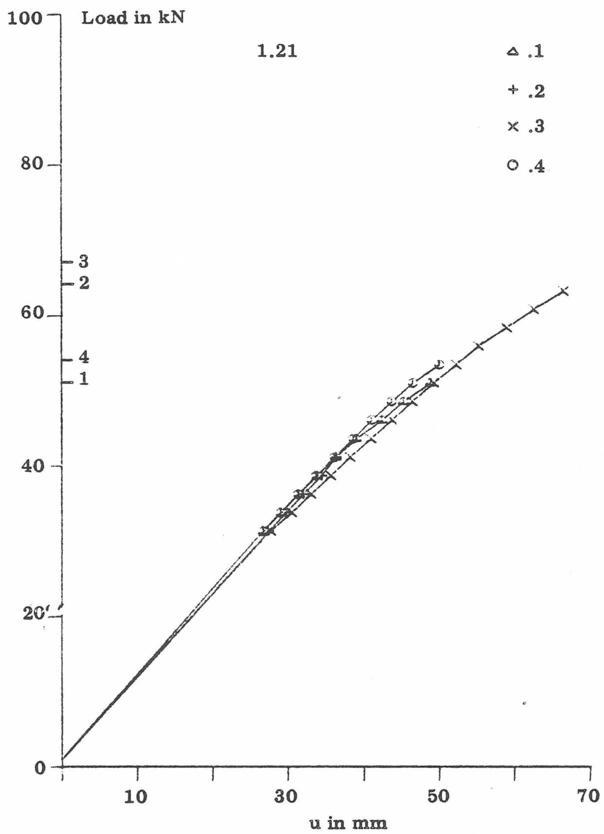
The abscissa is the directly measured deflection of the mid-point.

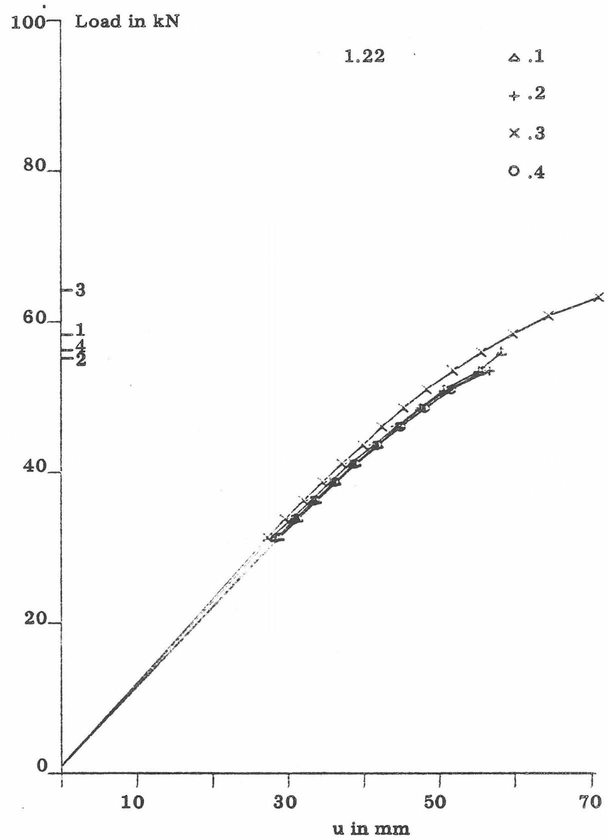


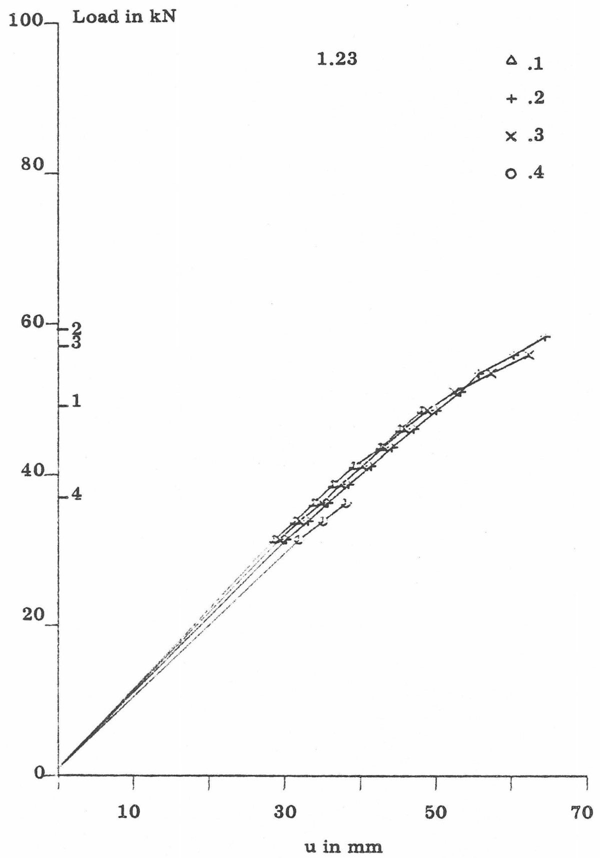


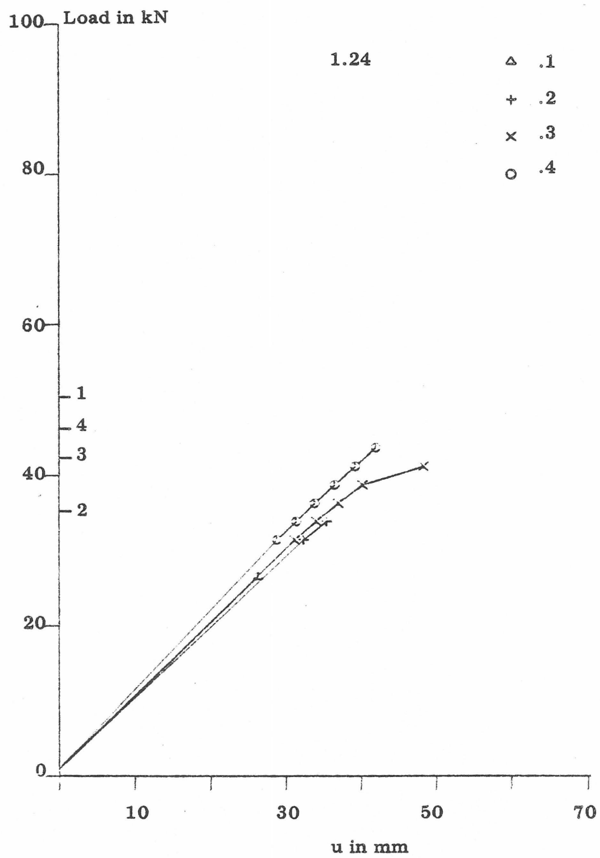


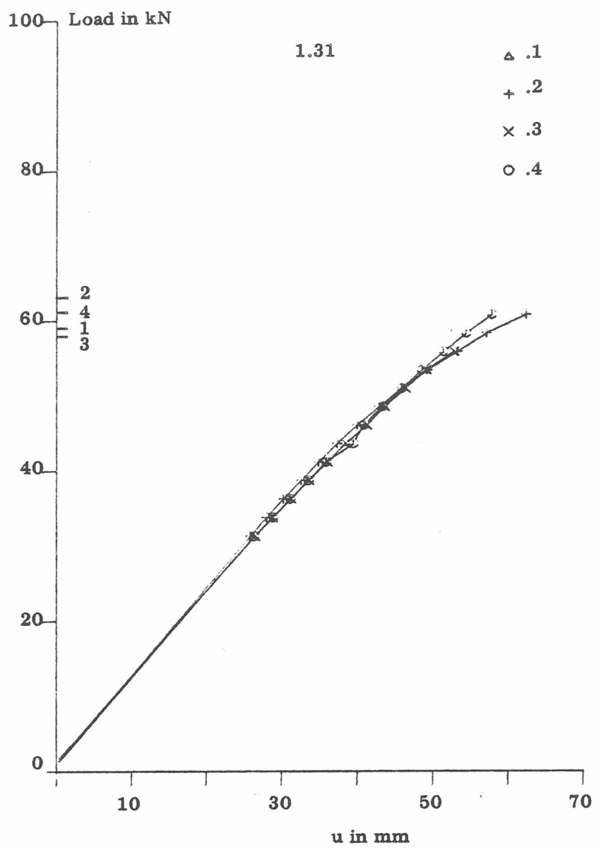



100
Load in kN
1.21
.1
.2
.3
.4
80
3
2
60
4
1
40
20
0
10
30
50
70
u in mm

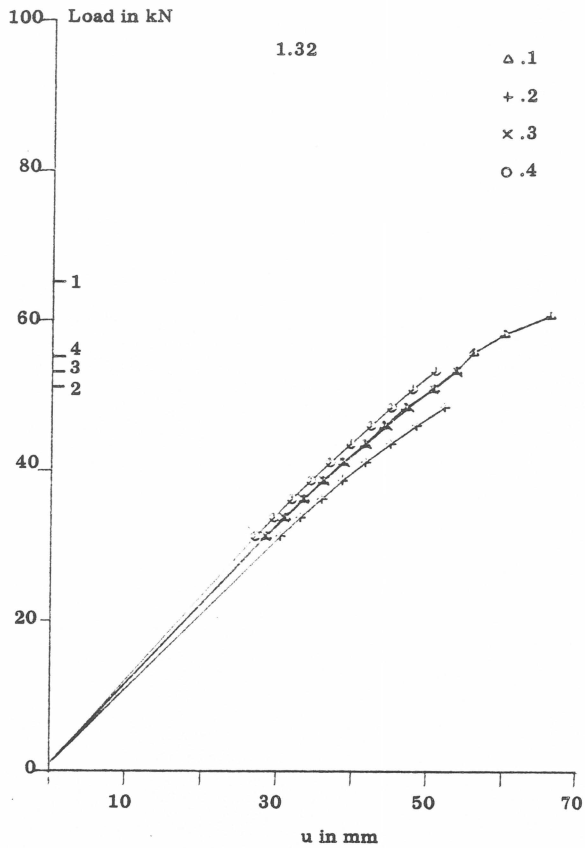

100
Load in kN
1.22
.1
.2
.3
.4
80
3
60
1
4
2
40
20
0
10
30
50
70
u in mm


100
Load in kN
1.23
.1
.2
.3
.4
80
60
2
3
1
40
4
20
0
10
30
50
70
u in mm

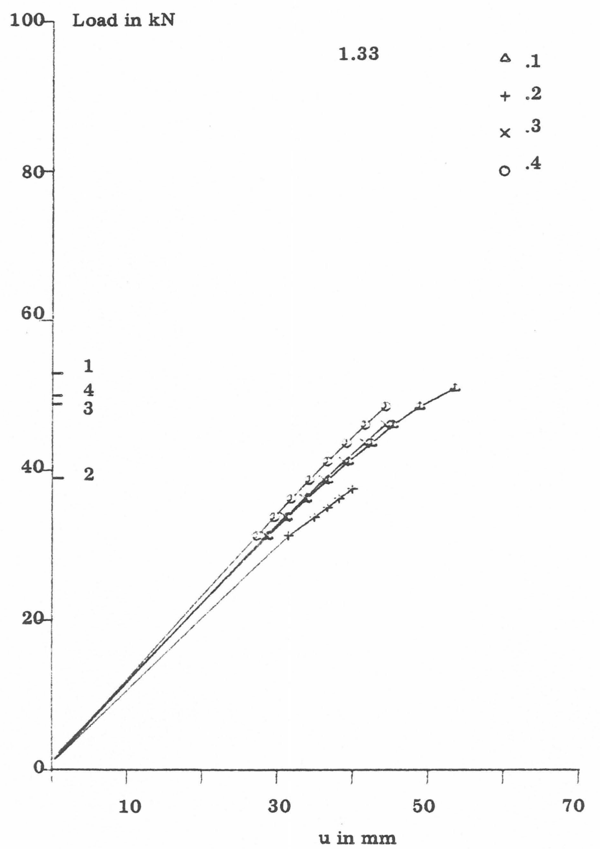

100
Load in kN
1.24
.1
.2
.3
.4
80
60
1
4
3
40
2
20
0
10
30
50
70
u in mm



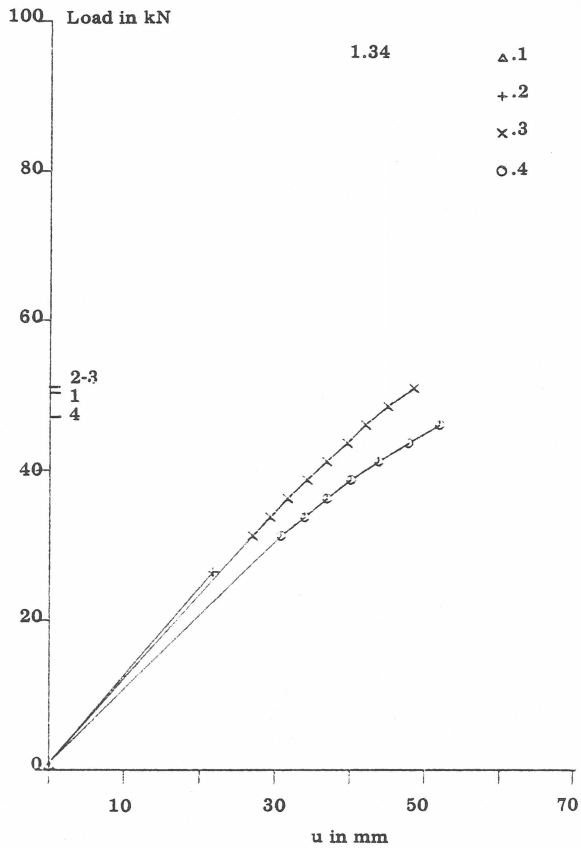
Load in kN
1.31
.1
.2
.3
.4
2
4
1
3
u in mm



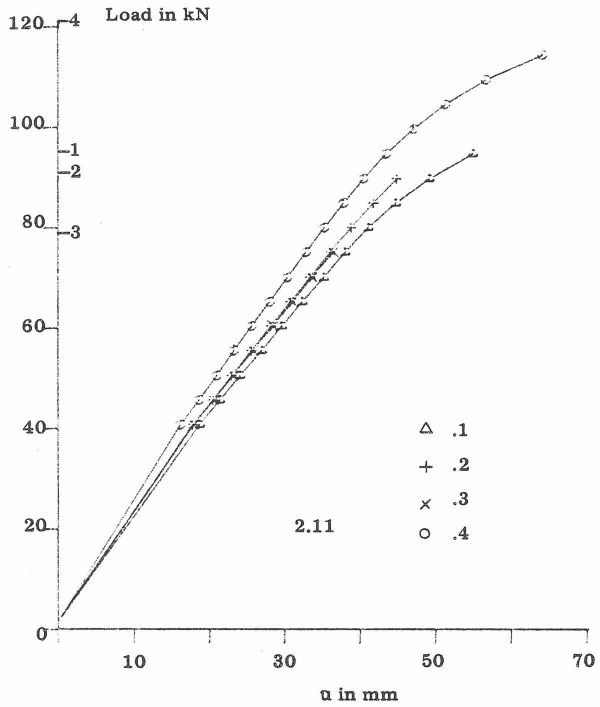
Load in kN
1.32
.1
.2
.3
.4
1
4
3
2
u in mm

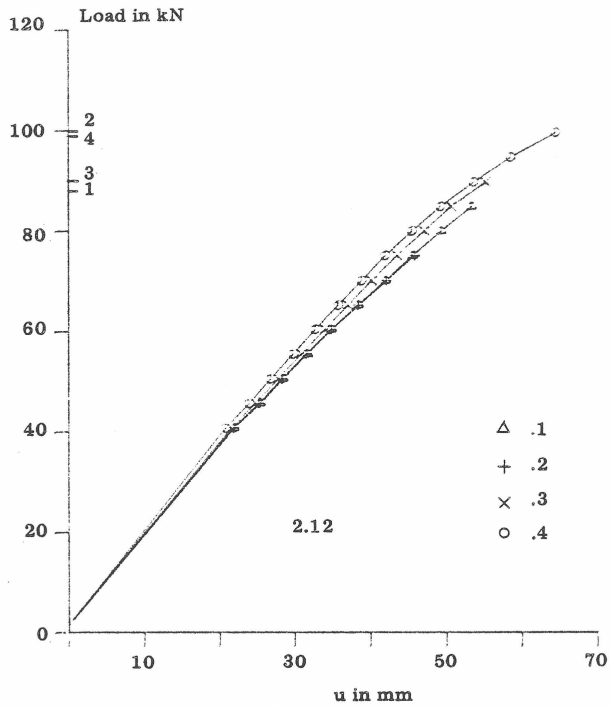


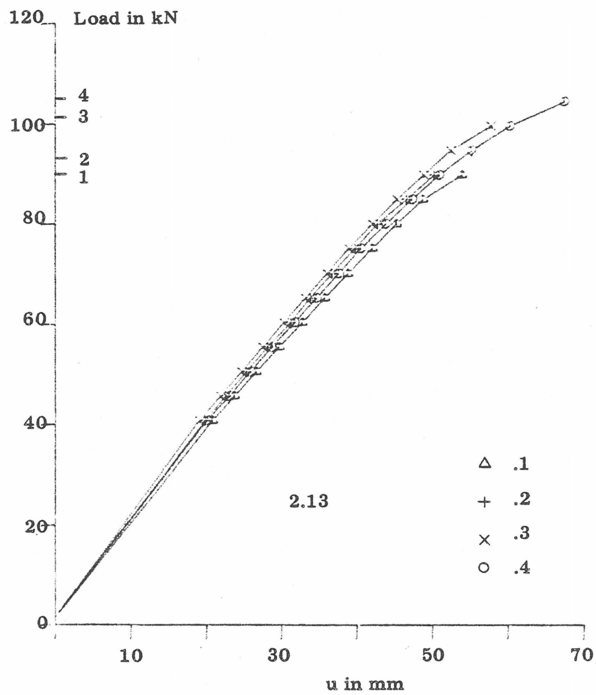
Load in kN
1.33
.1
.2
.3
.4
1
4
3
2
u in mm

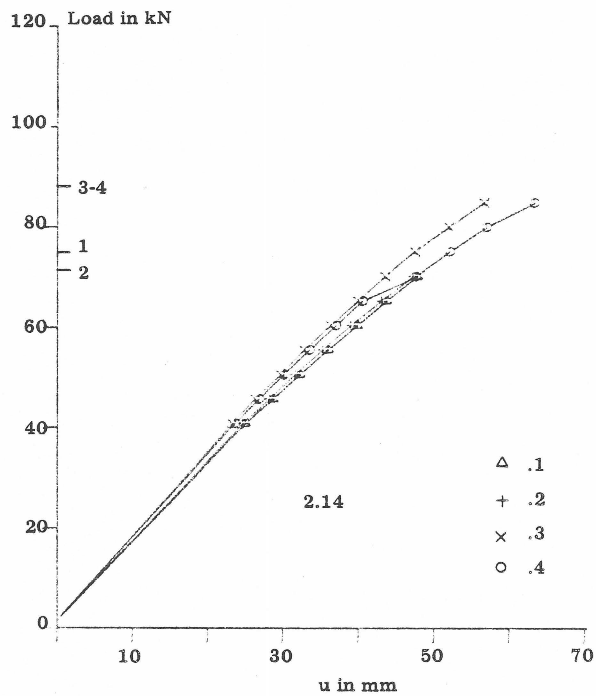


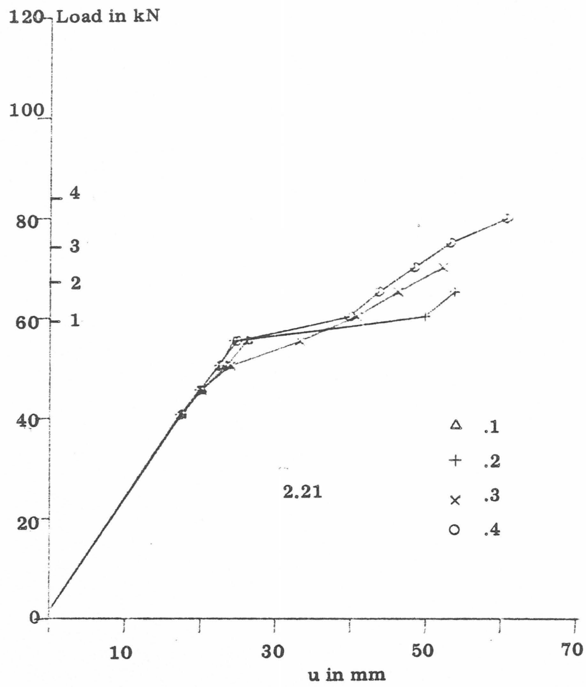
Load in kN
1.34
.1
.2
.3
.4
2-3
1
4
u in mm


Load in kN
120
100
80
60
40
20
0
4
1
2
3
10
30
50
70
u in mm
2.11
△ .1
+ .2
× .3
○ .4

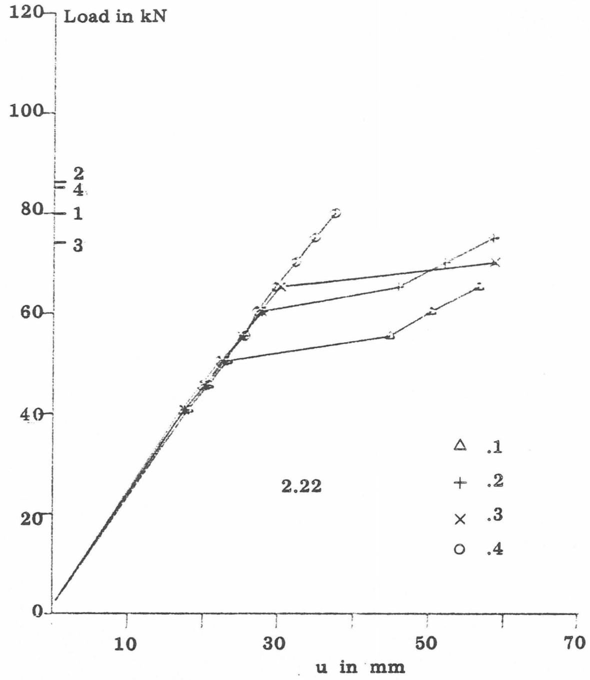

Load in kN
120
100
80
60
40
20
0
2
4
3
1
10
30
50
70
u in mm
2.12
△ .1
+ .2
× .3
○ .4


Load in kN
120
100
80
60
40
20
0
4
3
2
1
10
30
50
70
u in mm
2.13
△ .1
+ .2
× .3
○ .4

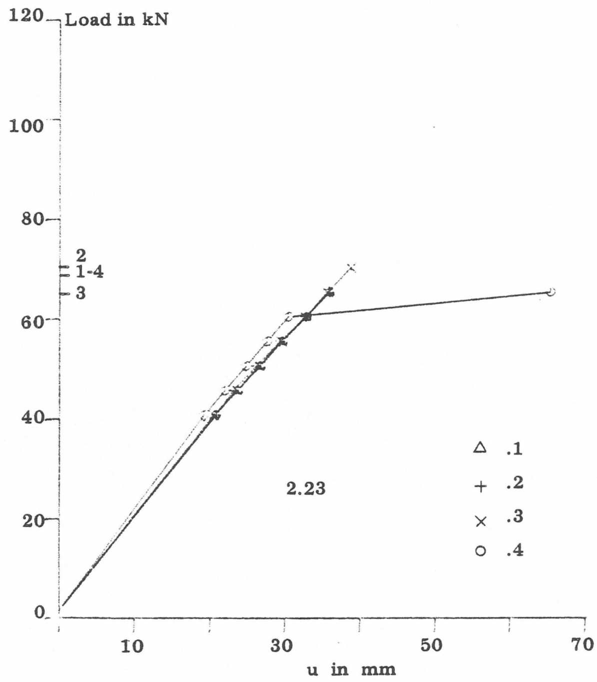

Load in kN
120
100
80
60
40
20
0
3-4
1
2
10
30
50
70
u in mm
2.14
△ .1
+ .2
× .3
○ .4



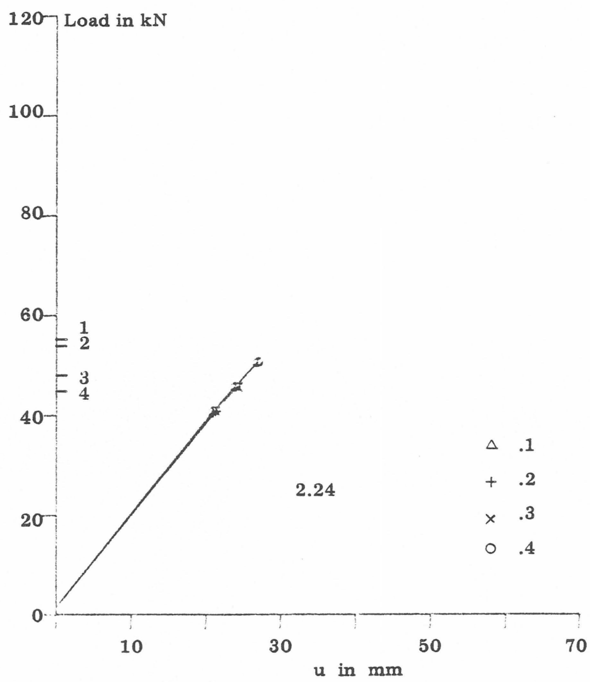
Load in kN
120
100
80
60
40
20
0
4
3
2
1
△ .1
+ .2
× .3
○ .4
2.21
10
30
50
70
u in mm



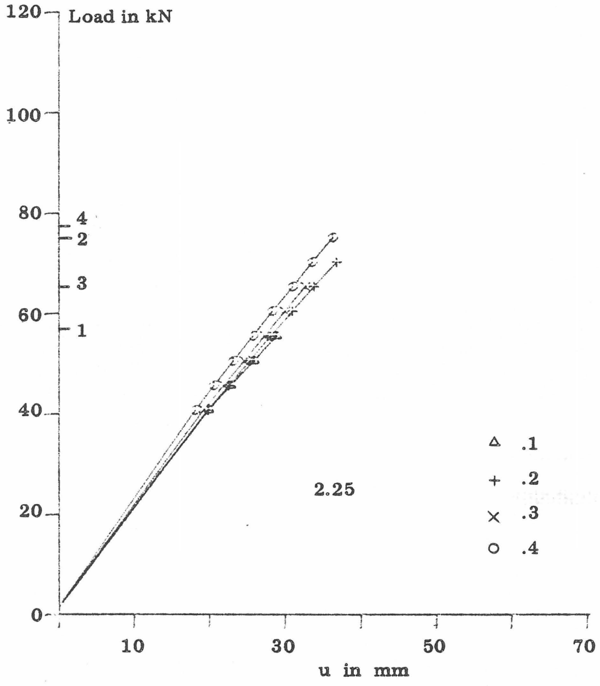
Load in kN
120
100
80
60
40
20
0
2
4
1
3
△ .1
+ .2
× .3
○ .4
2.22
10
30
50
70
u in mm

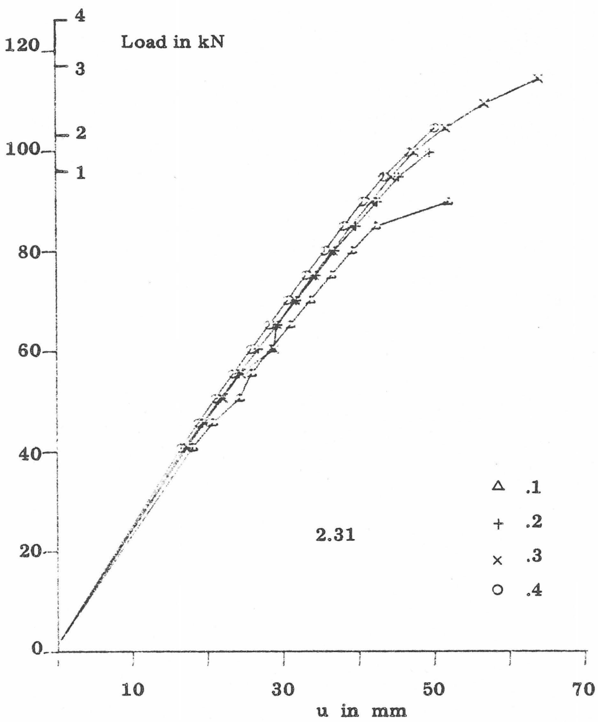


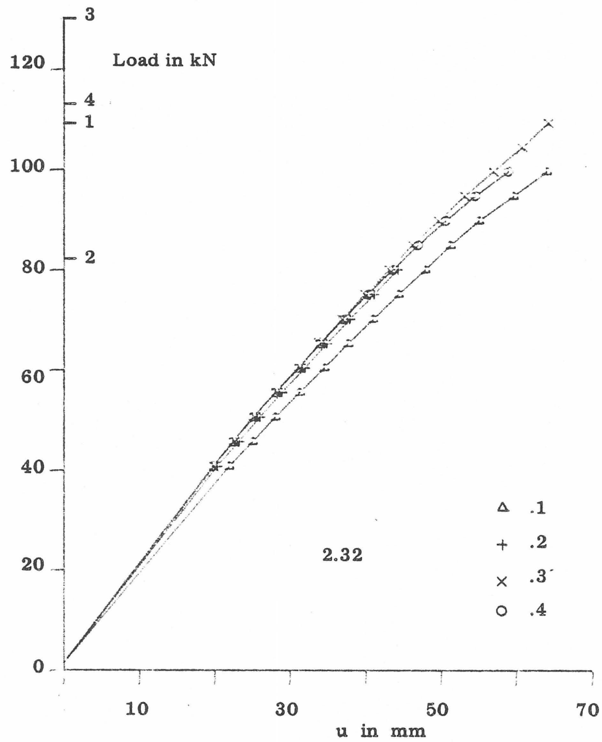
Load in kN
120
100
80
60
40
20
0
2
1-4
3
△ .1
+ .2
× .3
○ .4
2.23
10
30
50
70
u in mm

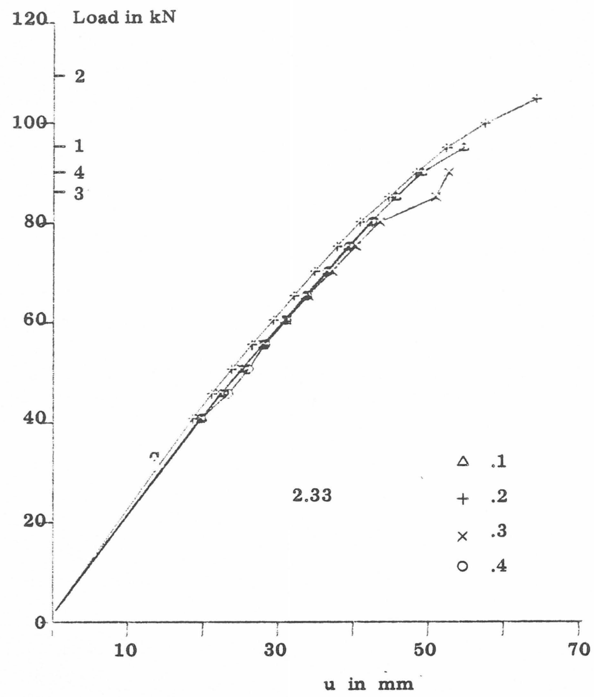


Load in kN
120
100
80
60
40
20
0
1
2
3
4
△ .1
+ .2
× .3
○ .4
2.24
10
30
50
70
u in mm

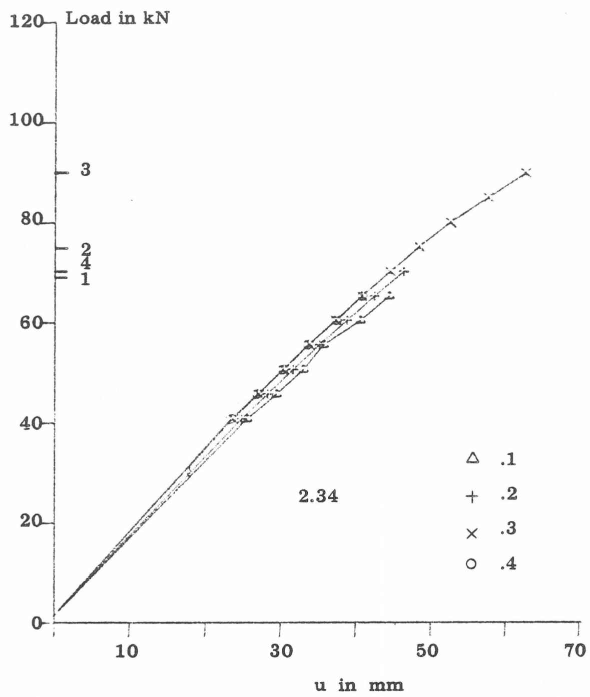

Load in kN
120
100
80
60
40
20
0
4
2
3
1
2.25
.1
.2
.3
.4
10
30
50
70
u in mm


Load in kN
120
100
80
60
40
20
0
4
3
2
1
2.31
.1
.2
.3
.4
10
30
50
70
u in mm

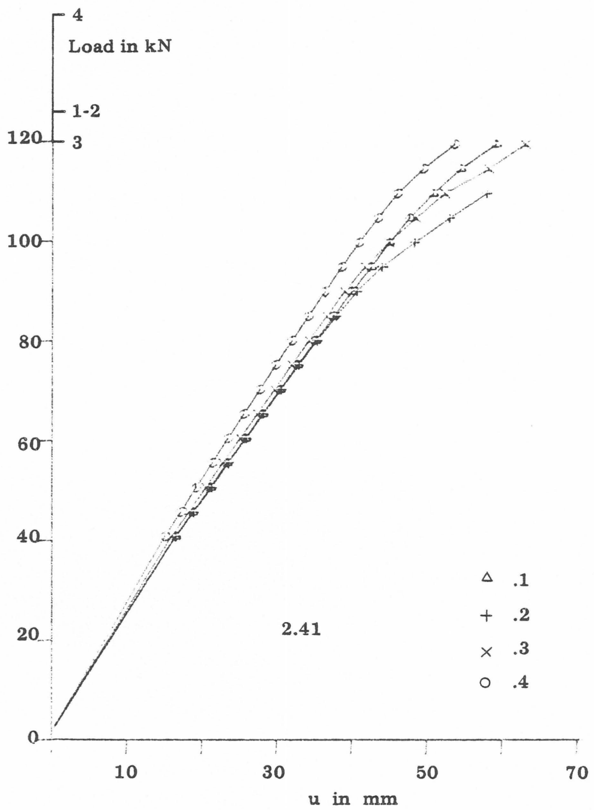

Load in kN
120
100
80
60
40
20
0
3
4
1
2
2.32
.1
.2
.3
.4
10
30
50
70
u in mm



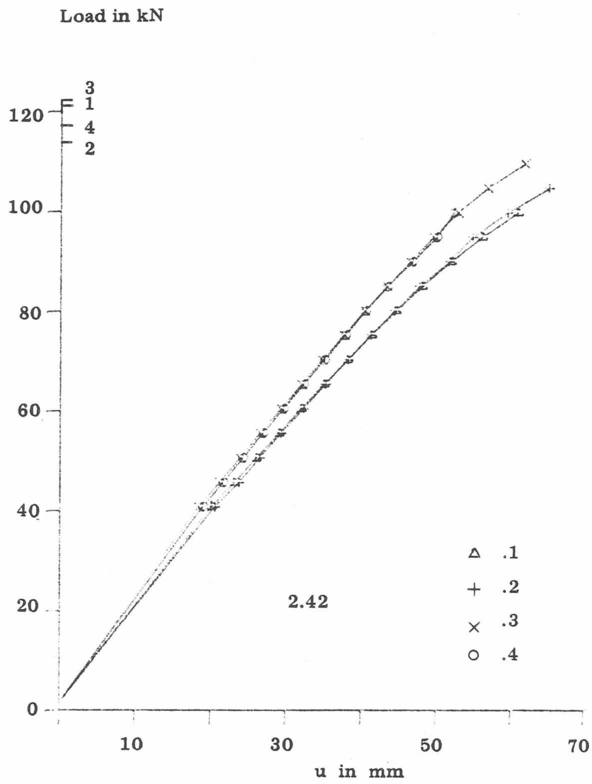
Load in kN
120
100
80
60
40
20
0
2
1
4
3
10
30
50
70
u in mm
2.33
△ .1
+ .2
× .3
○ .4



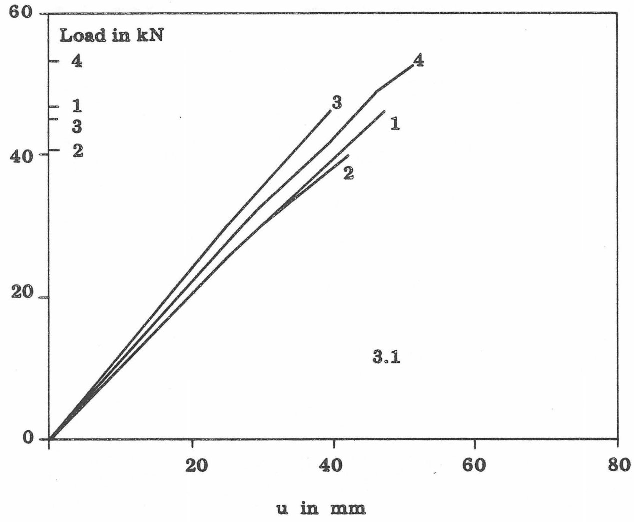
Load in kN
120
100
80
60
40
20
0
3
2
4
1
10
30
50
70
u in mm
2.34
△ .1
+ .2
× .3
○ .4



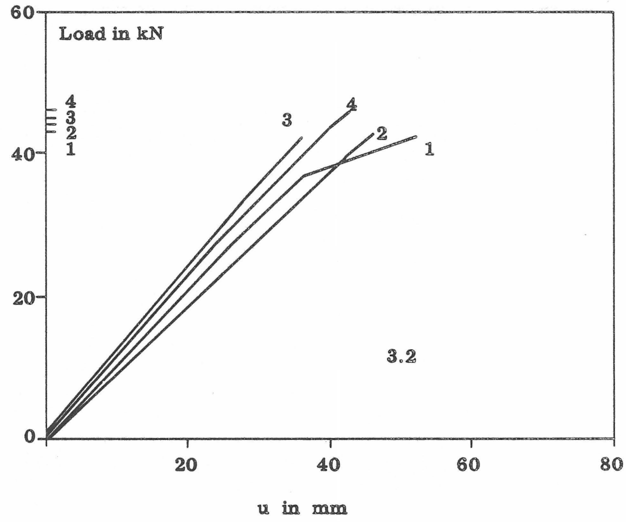
4
Load in kN
1-2
3
120
100
80
60
40
20
0
10
30
50
70
u in mm
2.41
△ .1
+ .2
× .3
○ .4



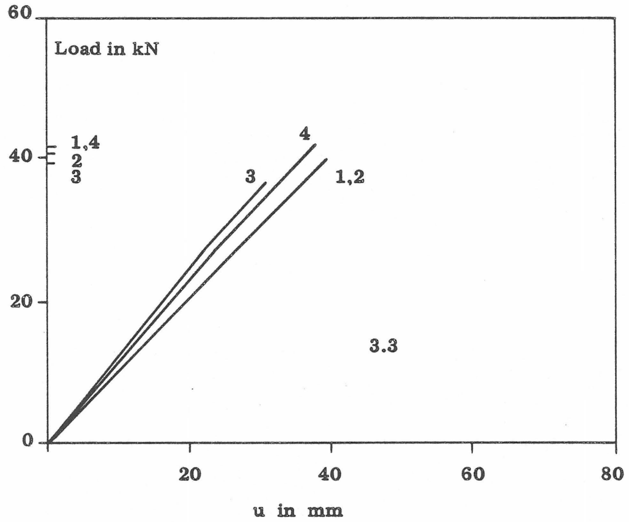
Load in kN
3
1
4
2
120
100
80
60
40
20
0
10
30
50
70
u in mm
2.42
△ .1
+ .2
× .3
○ .4



60
Load in kN
4
1
3
2
40
20
0
3
4
1
2
3.1
20
40
60
80
u in mm



60
Load in kN
4
3
2
1
40
20
0
3
4
2
1
3.2
20
40
60
80
u in mm



60
Load in kN
1,4
2
3
40
20
0
4
3
1,2
3.3
20
40
60
80
u in mm

LIMTRÆBJÆLKERS STYRKE (STRENGTH OF GLUED LAMINATED BEAMS):

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