CIB-W18/26-12-1

INTERNATIONAL COUNCIL FOR BUILDING RESEARCH STUDIES AND DOCUMENTATION

WORKING COMMISSION W18 - TIMBER STRUCTURES

NORWEGIAN BENDING TESTS WITH GLUED LAMINATED BEAMS -COMPARATIVE CALCULATIONS WITH THE "KARLSRUHE CALCULATION MODEL"

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MEETING TWENTY - SIX

ATHENS, GEORGIA

USA

AUGUST 1993

Norwegian Bending Tests with Glued Laminated Beams

- Comparative Calculations with the "Karlsruhe calculation model"

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1 Introduction

In 1990 and 1991 extensive and systematic studies on the strength of glued laminated beams (glulam beams) have been carried out at the "Norwegian Institute of Wood Technology" in Oslo/Norway (Falk, Solli, Aasheim 1992). It was aimed to obtain given strength values by variation of the properties of the laminations (density and modulus of elasticity).
The investigations described in this paper were performed to estimate and to predict the bending strengths of these glulam test beams with the "Karlsruhe calculation model" (Colling, Ehlbeck, Görlacher). The calculations were based on the informations made available and described in section 2. The test results (bending strength and modulus of elasticity) obtained in Oslo were unknown before finalizing the calculations and publishing the results.

Altogether, three different combinations of different built-up have been studied. In all cases the beam depth was 300 mm with nine laminations of 33,3 mm nominal thickness. The three beam combinations are shown in **Fig. 1.** The test set-up is illustrated in **Fig. 2.**

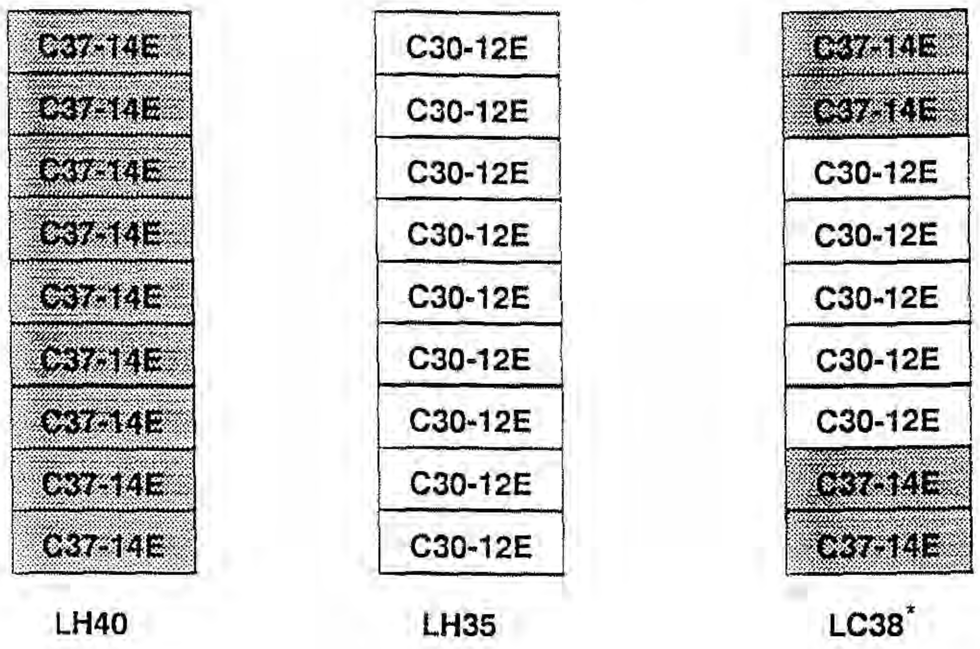

Fig 1: Beam combinations tested

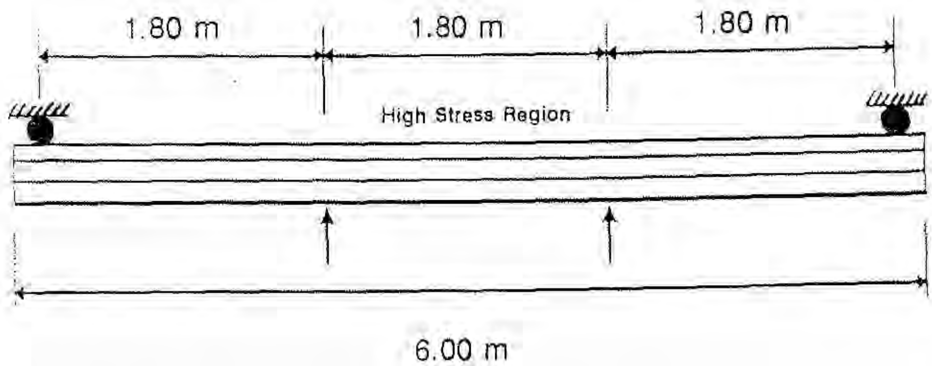

Fig 2: Beam test configuration

2 Input data for the calculation model

2.1 Knots

No information has been submitted about the knots and their distribution along the board length. Therefore it was assumed that the KAR-values (KAR = Knot Area Ratio) within the board sections (cells) correspond approximately to a minimum quality given by the S 10-grade of the German standard DIN 4074. Thus, it was fixed a value of max KAR = 0,55.

2.2 Density

The "Karlsruhe calculation model" is based on regression equations including the oven-dry density of board sections (called "cells") of 15 cm length, but not on the overall mean density of the board at a moisture content of 12 %.

In the simulation calculations performed a constant density along the whole length of each board was assumed, i.e. for simplification it was assumed that all cells of one board have the same density (equal to the overall mean density of the board).
For each board a value of DEN_{12} (density at 12 % m.c.) was randomly chosen from the given density distribution function of the appertaining strength class (**Table 1**). From this value the DEN_0-value (oven-dry density) - which was needed for the simulation calculation - was calculated from the expression:

$$DEN_0 = \frac{DEN_{12}}{1 + m.c. - 0,00085 \cdot DEN_{12} \cdot m.c.} \qquad \text{with m.c.} = 0,12 \qquad (1)$$

2.3 Modulus of elasticity (MOE)

For determination of MOE of the laminations all laminations were machine-graded (Computermatic MK-IV) in that way that under flatwise bending the MOE-values were obtained in sections. MOE in this context is defined, however as the mean MOE of the board, calculated from the single values of the board sections (**Table 1**).
In the Karlsruhe calculation model the MOE-values in tension of each cell are calculated on the basis of regression equations; from these single values the mean MOE of the board in tension are calculated. This simulated MOE-value of each board is compared with a preconceived value; in case this value does not fit into a certain tolerance limit (± 5 %) the simulation calculation for this board shall be repeated. This presumes that the procedures to simulate as well as to preconceive the MOE-value

correspond to each other. This is, however, not the case with the test material under scrutiny.

Therfore, the machine stress graded bending- MOE had to be adopted to the tension-MOE-values on which the Karlsruhe model is based.

In **Fig. 3** the MOE over mean density is shown. The data came from investigations in Karlsruhe with more than 1000 boards taken from several German glulam production plants. The MOE-values were obtained from a procedure based on measuring the longitudinal vibration time of the boards. Multiplying the Norwegian data of MOE - determined with a machine stress grader in Norway - with a factor of 1,27 results in a regression line practically identical with the regression line obtained with the Karlsruhe test procedure (see Fig. 3).

The difference between the MOE values of about 27 % can be explained by mainly two reasons:

- the machine graded MOE is significantly lower than the real (laboratory tests) MOE (10 - 15 %)
- the dynamic MOE determined by longitudinal vibrations (Karlsruhe model) is about 5 % (tension) to 10 % (bending) higher than the MOE determined by static tests

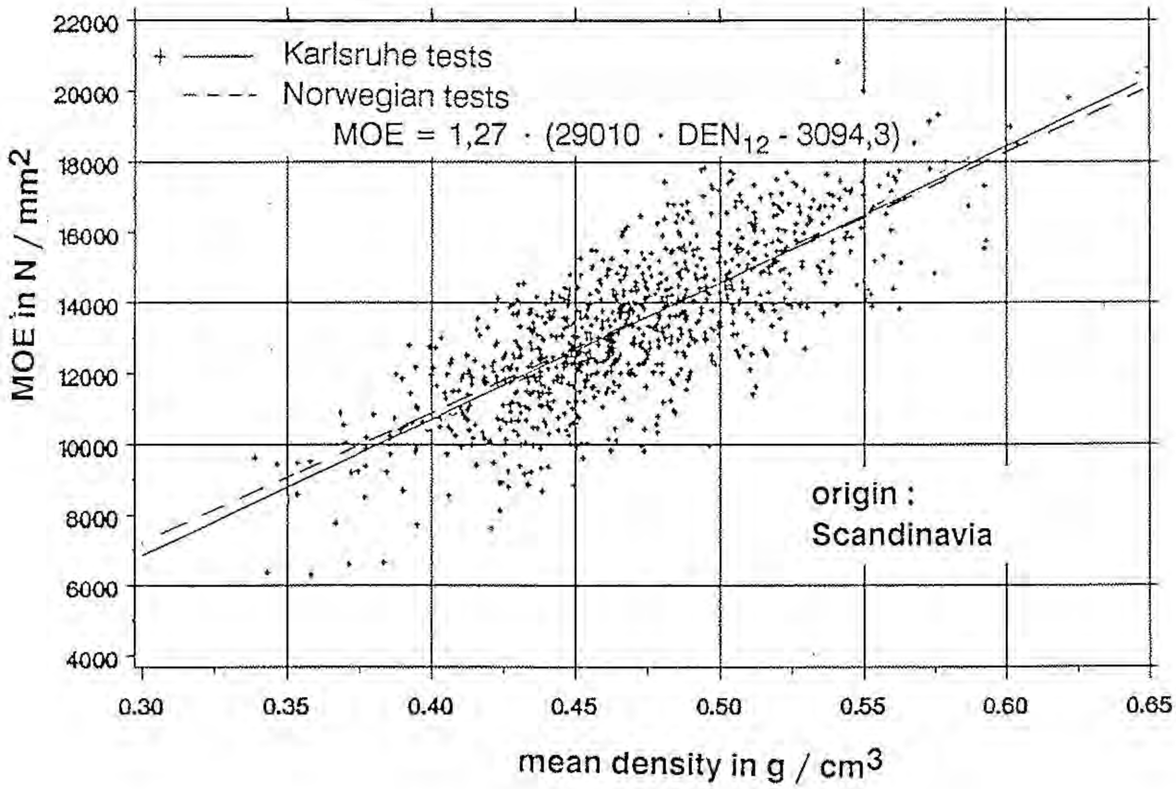

Fig 3: Regression between average density and MOE

For this reason, in the simulation calculations for the boards one value was chosen from the distribution function of the MOE of the appertaining strength class and multiplied by a factor of 1,27 before using it as a comparative value in the subsequent strength and stiffness calculations.

Table 1: Parameter estimates for established C30-12E and C37-14E lamination Grades

		Weibull Parameters			Lognormal Parameters		
		Shape	Scale	Loc.	Mean	S.D.	Loc.
C30-12E	Density				5,586	0,1358	208,9
	MOE_{mac}	7,141	8639,3	2316,5			
	$f_{t,fj}$	3,48	17,67	19,91			
C37-14E	Density				5,739	0,1308	208,86
	MOE_{mac}				8,871	0,2282	6077,9
	$f_{t,fj}$	4,631	24,37	15,37			
	Length	5,56	271,38	180,0			

2.4 Board length

The simulation of the board lengths happened by chance using the frequency distribution given in Table 1.

2.5 Finger-joint strength

For the simulation calculations the finger-joint tensile strength was simulated in two different manners:

- on the one hand to each finger-joint a tensile strength value was assigned by using the distribution given in Table 1,
- on the other hand the finger-joint tensile strength values were calculated by means of existing regression equations.

The reason for this was as follows:
The Norwegian tests to obtain the finger-joint tensile strength values were carried out by using a test set-up with the clamping device being hinge-mounted fastened to the cross-head of the testing machine. Thus, any lateral deformations due to structural imperfections of the boards were inevitably possible. These lateral deformations cause additional moments in the test piece and lead to a reduction of the tensile strength by way of simplified calculation.

The regression equations used in the "Karlsruhe calculation model" were found out, however, by using a test set-up which prevents any lateral deformation by means of a rigid clamping device. This test method simulates the situation in a glulam beam in which the single laminations are prevented to deform laterally by the adjacent lamellations rigidly glued.

Based on tests performed in Karlsruhe and Munich the finger-joint tensile strength can be calculated by using the following relationship:

$$\ln(f_{t,fj}) = 2{,}72 + 6{,}14 \cdot 10^{-5} \cdot MOE_{t,fj} \qquad r = 0{,}58 \qquad (2)$$

The variation of the residuum is taken into account for the simulation calculations by assuming a Gaussian distribution with a mean of zero and a standard deviation of 0,195.

This equation (2) was derived from 235 test results with finger-joint profiles of 20 mm length. Recent investigations in Germany have proved a 5 to 10 % strength increase for profiles of 15 mm length. Therefore, the strength values obtained from equ. (2) were multiplied by a factor of 1,07 assuming a 7 % strength increase.

A regression equation for determining the tensile MOE of finger-joints was derived as follows:

$$\ln(MOE_{t,fj}) = 8{,}407 + 2{,}63 \cdot 10^{-3} \cdot DEN_{0,min} \qquad r = 0{,}64 \qquad (3)$$

with $DEN_{0,min}$ in kg/m^3 as the smaller of the two oven-dry densities of the two pieces (boards) jointed by the finger-joint.

The variation of the residuum is taken into account by assuming a Gaussion distribution with a mean of zero and a standard deviation of 0,135.

In order to estimate the effect of these different ways of allocating the finger-joint tensile strength values on the simulation results, the calculations were carried out by using equs. (2) and (3) as well as by randomly assigning the finger-joint tensile strength values from the distributions given in Table 1, respectively.

3 Simulation calculations

The following parameters were varied:

- *Beam layup*
  As shown in Fig. 1 three different combinations were studied
- *Density, modulus of elasticity*
  For each lamination class the appertaining boards were simulated by assuming the density and the modified MOE distribution according Table 1 and section 2.3
- *Finger-joint strength*
  The tensile strength of the finger-joints was taken into account once on the basis of the distribution (DIS) of test results (table 1) and on the other hand by using the regression analysis (REG), see section 2.5.

In the Norwegian test programme in total 100 bending tests were carried out with each beam combination. Therefore, for each beam combination and variant a sample of 100 beams was simulated and the bending strength of each beam was predicted by the "Karlsruhe calculation model". In order to check in which range the test results may vary, for each of the 6 variants three series of 100 beams were simulated.

3.1 Simulation results

Strength values

An outline of the results is given in **Tables 2 to 4** with the 5-percentiles calculated assuming a Gaussian distribution. This was justified in all cases (Kolmogorov-test).

Comparison of the series DIS against REG

A comparison of the series belonging together, e.g. series DIS and REG, leads to the following tendencies:

- beams belonging to DIS-series demonstrate lower mean values as well as 5-percentiles of the bending strength,
- beams belonging to DIS-series give more finger-joint failures as those belonging to REG-series.

These findings can be explained with the differently assumed distributions of the finger-joint tensile strengths as described in section 2.5.

Table 2: Simulation results (LH 40)

simulations series	all beams			beams with finger-joint failure			beams with wood failure		
	m	v	x_5	N	m	v	N	m	v
	N/mm^2	%	N/mm^2		N/mm^2	%		N/mm^2	%
DIS	47,8	17,9	33,7	68	45,7	18,3	32	52,2	14,1
	48,5	16,8	35,1	50	45,7	18,5	50	51,4	13,3
	46,7	19,3	31,9	57	43,5	17,7	43	50,9	17,7
REG	51,6	16,4	37,7	39	49,0	19,8	61	53,2	13,6
	52,4	16,2	38,4	35	50,4	18,7	65	53,5	14,6
	51,8	17,4	37,0	34	47,4	17,6	66	54,0	15,7

Table 3: Simulation results (LH 35)

simulations series	all beams			beams with finger-joint failure			beams with wood failure		
	m	v	x_5	N	m	v	N	m	v
	N/mm^2	%	N/mm^2		N/mm^2	%		N/mm^2	%
DIS	40,4	15,1	30,4	54	39,4	15,8	46	41,6	14,0
	40,4	17,0	29,1	58	39,4	19,2	42	41,7	13,4
	41,5	15,4	31,0	45	39,8	18,0	55	43,0	12,5
REG	41,6	15,8	30,8	36	38,3	16,6	64	43,4	13,8
	43,0	15,8	31,8	33	40,9	16,3	67	44,0	15,2
	43,3	14,6	32,9	33	41,4	15,7	67	44,2	13,7

Table 4: Simulation results (LC 38)

simulations series	all beams			beams with finger-joint failure			beams with wood failure		
	m	v	x_5	N	m	v	N	m	v
	N/mm^2	%	N/mm^2		N/mm^2	%		N/mm^2	%
DIS	44,8	18,4	31,2	60	41,6	17,9	40	49,7	13,9
	45,7	18,7	31,6	61	42,6	18,0	39	50,5	15,1
	47,4	20,0	31,8	65	44,8	20,8	35	52,2	15,2
REG	49,6	16,8	35,9	41	46,9	18,7	59	51,4	14,7
	50,5	16,7	36,6	36	49,3	18,8	64	51,1	15,5
	49,9	16,3	36,5	34	47,1	18,9	66	51,3	14,4

3.2 Comparison with the Norwegian bending tests

The strength values given in **Table 5** can be expected for the three beam combinations tested. These values are based on the simulation calculations of the series called REG, because in this case the narrow correlation between strength and MOE is taken into account for the boards (laminations) as well as for the finger-joints. Moreover, any imponderabilities in connection with the determination of the finger-joint tensile strength by means of the test device used are excluded.
The strength values of the Norwegian bending test are also given in Table 5. In all cases there is a very good agreement between the calculated and the tested values especially between the values of the 5-percentiles.

Table 5: Predicted and tested beam bending strengths

beam combination		mean value	5-percentile (non-parametric)
		N/mm^2	N/mm^2
LH 40	"Karlsruhe calculation model"	51,9	38,7
	Norwegian bending tests	52,5	39,4
	quotient	**0,99**	**0,98**
LH 35	"Karlsruhe calculation model"	42,6	32,7
	Norwegian bending tests	44,3	32,8
	quotient	**0,96**	**1,00**
LC 38	"Karlsruhe calculation model"	49,6	37,5
	Norwegian bending tests	47,7	37,9
	quotient	**1,04**	**0,99**

6 Summary

In 1990 and 1991 extensive and systematic studies on the strength of glued laminated beams have been carried out at the " Norwegian Institute of Wood Technology" in Oslo. For this purpose the mechanical properties of the laminations were determined and classified according to CEN draft standards of that time (C30-12E and C37-14E). Glued laminated test beams following different strength classes (LH 35, LH40 and LC38) were constructed and tested in strength and stiffness.
At the same time strength and stiffness values of these beams were calculated independently by means of the Karlsruhe calculation model. Informations about the properties of the laminations i.e. the statistical distribution of density and modulus of elasticity of the boards used for the three different combinations, about the finger-joints, and about the built-up of the beams were known from the Norwegian pre-tests. The results of the beam tests were kept secret until the predictive calculations were available.
The strength of all beam combinations (mean value and 5-percentile) were proved to be in very good agreement with the calculated values (within 4 % deviation). By this study it became once more evident that the Karlsruhe calculation model is suitable to predict the strength of glued laminated beams. It is on that account an appropriate aid for the evaluation of standards on strength classes for glulam based on the relevant properties assigned to the laminations and the finger-joints.

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