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THE DEPENDENCE OF THE BENDING STRENGTH ON THE GLUED LAMINATED TIMBER GIRDER DEPTH

by

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1. Introduction

With a view to determining the influence of the girder depth on the bending strength of glued laminated timber, experimental investigations and tests are being carried out. It is the objective of these tests and investigations to find out data and information concerning the application of the "depth dependence" modification factor k_h (depth factor) for glued laminated timber (abbreviated hereinafter referred to as: BSH in German or GLT in English, respectively).

2. Objective of the experimental investigations

Due to the interrelation or connection between the girder depth and the bending strength of GLT girders which is yet obscure, experimental investigations are required. Publications by Ehlbeck and Colling (see the bibliographical references /1/ and /2/) are verifying that in the case of GLT girders with which the failure was to be attributed to a key-dovetail connection or "finger joint" (abbreviated hereinafter referred to as: KDC in English or KZ in German, respectively) no dependence of the bending strength on the girder depth could be determined. The bending strength of the GLT girders was within the order of magnitude of the tensile strength of the KDC.
Thus, according to this the introduction and application of a so-called "depth factor" seems not to be justified.
The bending strength of GLT girders is being influenced by two independent factors, i.e. the timber strength and the KDC strength.
A stricter visual sorting is not influencing the KDC (or "finger joint") strength.
Only a mechanical sorting based on the bulk density or the modulus of elasticity of the boards is likely to provide increased KDC strengths as well.
Below the girder depth of 500 mm, the bending strength of the GLT girders being free from KDCs in the zone of maximum flexural

tension is decreasing (see /1/ and /2/).
Above the girder depth of 500 mm, there is no considerable decrease in bending strength.
With GLT girders the KDCs of which are failing, no interrelation between bending strength and girder depth is being determined.
Tests showed that GLT girders the KDCs ("finger joints") of which were failing had about the same bending strength with a girder depth of 330 mm as girders with a girder depth of 1,000 mm.

Schöne /3/ has investigated and tested the following two types of GLT girders:

(A) girders being provided with a KDC within the zone of maximum flexural tension;
(B) girders with which the zone of maximum flexural tension is free from KDC.

With the type (A) girders, the failure of the structural component was always occurring within the KDC area. The mean bending strength of the GLT girders is approximately equal to the mean tensile strength of the KDC. Consequently, a strength-increasing overlapping effect to be expected due to the KDC staggering can therefore not be verified /3/.

Since in the manufacture of GLT girders at the glued wood construction enterprises the location or position of the KDC ("finger joint") is a random event and the average length of the machined boards is hardly amounting to more than 2 metres, already with girders having a length as from about 6 metres the type (A) pattern is the normal case.

However, also with shorter girders the probability is very large that KDCs ("finger joints") are located within the heavily stressed zone.
Therefore, from the aspect of the real production of GLT girders, the application of the "depth factor" is rejected and the tensile strength of the KDCs is being regarded as the decisive feature.

Taking into account the data and information iidicated in the publications concerned with regard to the dependence of the bending strength of GLT girders on their depth, specific experimental studies and investigations are being accomplished. In this connection, the following two grades of glued laminated timber are being considered (see Figure 1):

"BSH 0"-type GLT
- the layers of boards are being sorted visually;
- the position of the key-dovetail connection (KDC) is random.

"BSH M 3"-type GLT
- the layers of boards are being sorted mechanically;
- the KDC ("finger joint") is located within the zone of maximum flexural tension.

3. Description of the test specimens

3.1. GLT girders of the "BSH 0"-type grade

For the short-term tests, the "BSH 0"-type girders as shown and described in the Figures 1, 4 and 5 are being used.
The layers of boards of the "BSH 0"-type glued laminated timber girders consist of sawn coniferous timber (pine) and are being sorted visually according to the knottiness into the quality class GK II as follows:

- individual knots according to Figure 2;
- accumulations of knots according to Figure 3.

The glueing (bonding) of the layers of boards with one another as well as of the KDCs ("finger joints") is being performed by using a "Plastasol Ĺ 47 N"-type phenolic resin bonding adhesive.

The position (place) of the KDC is at random. The key-dovetail ("finger joint") length is 20 mm. The distance of the KDCs (dovetail staggering; in German being abbreviated as KZV) between the 1st and 2nd layer of boards (see Figure 4) is being guaranteed with an amount of KZV = 250 mm.

The equilibrium moisture of the layers of boards after the manufacture amounts to $\omega \approx 12$ %.

3.2. GLT girders of the "BSH M 3"-type grade

For the short-term tests, the "BSH M 3"-type girders as shown and described in the Figures 1, 4 and 6 are being used.
The layers of boards of the "BSH M 3"-type glued laminated timber girders consist of sawn coniferous timber (pine) and are being sorted mechanically according to the modulus of elasticity in bending and to the knottiness into strength classes as follows:

- external layers (see Figure 1) are falling under the strength class F II
  ($E \geqq 9{,}500\ N/mm^2$; individual knots according to Figure 2, accumulations of knots according to Figure 3; see /4/);
- internal layers (see Figure 1) are falling under the strength class F III
  ($E \geqq 7{,}000\ N/mm^2$; individual knots according to Figure 2, accumulations of knots according to Figure 3; see /4/).

Decisive for the allocation to a strength class is the unfavourable value of one sorting parameter.

The glueing (bonding) of the layers of boards with one another as well as of the KDCs ("finger joints") is being performed by using a "Plastasol L 47 N"-type phenolic resin bonding adhesive.

As a general principle, a KDC ("finger joint") is being arranged in layer 1 (being the lowest girder layer - the tension layer -; see Figure 1) within the test zone (see Figure 4).

The key-dovetail ("finger") length amounts to 50 mm. The distance of the KDCs (dovetail staggering; in German: KZV) between the 1st and 2nd layer is being guaranteed with an amount of KZV $\geqq$ 250 mm.

The equilibrium moisture of the layers of boards after the manufacture amounts to $\omega \approx 12\ \%$.

4. Test procedure

With a view to achieving a zone being free from transverse forces, a four-point loading is being selected for the test arrangement of the GLT girders (see Figure 4).

The results and findings from studies and investigations performed by using structural timber (see /5/) are showing that - in order to avoid shear failures - the ratio of the flexural stress $\sigma_{m,d}$ to the shear stress τ_d shall be 22 whereas for a shear influence of about 6 % the ratio of the effective span l_1 to the specimen height h shall be 15.

With these prerequisites prevailing, the length of the test zone l_2 is being designed as $l_2 = 4\ h$ /5/ (see Figure 4).

The load is being applied by increments in such a way that the failure will occur after a loading period of 3 to 5 minutes.

The tests are being carried out at an air temperature of T = 20 °C, a relative air humidity of φ = 65 % and a timber moisture of ω = 12 %.

The girder deflection U_z is being measured at the central position of the effective span by means of a dial gauge.

5. Test evaluation

5.1. Bending tests by using "BSH 0"-type GLT girders

The test results are indicated in Figure 5.

The following two types of failure are distinguished:

A) tensile failure in the KDC ("finger joint") within the test zone l_2, layer 1 (see Figure 4);

B) tensile failure in the knot or timber within the test zone l_2, layer 1 (see Figure 4).

For the failure type A, the mean values of the bending strength $f_{m,mean}$ are not showing any dependence on the girder depth (see Figure 5).

For the failure type B, the reduction of $f_{m,mean}$ is occurring up to h = 608 mm but no longer beyond this depth.

The characteristic value of the bending strength (5%-quantile) $f_{m,k}$ was obtained from the Gauss normal distribution by conversion from small to large random sample numbers /6/.

With the characteristic values of the bending strength $f_{m,k}$, a reduction is occurring for the failure type A up to h = 608 mm and no more beyond that (see Figure 5).
As for the failure type B, the reduction is also occurring up to h = 608 mm and no more beyond that.

5.2. Bending tests by using "BSH M 3"-type GLT girders

The test results are indicated in Figure 6.

With the mean values of the bending strength $f_{m,mean}$, no reduction is occurring up to h = 608 mm in the case of the falure type A whereas a reduction can be perceived in the case of the failure type B.

Similar findings are being obtained with regard to the characteristic values of the bending strength $f_{m,k}$ as well.

5.3. Evaluation of the results and findings

The insignificant number of random samples as well as the interaction of different influences are only admitting of a limited statement.
Nevertheless, from the data and particulars included in the bibliography and based on our specific tests and investigations the following tendency becomes apparent:

With the characteristic values of the bending strength $f_{m,k}$, a reduction is occurring for the failure type A with "BSH 0"-type glued laminated timber up to h = 608 mm and no more beyond that.

An explanation concerning this may be as follows:

According to Ehlbeck /2/, with a KDC (i.e. key-dovetail connection or "finger joint") the tensile strength amounts to 80 % of the bending strength:

$$f_{t,o,k;fi} \sim 0.8\ f_{m,k;fj}$$

In the case of one dovetailed layer of boards pure flexural stressing with the corresponding bending strength $f_{m,k}$ is prevailing whereas in the KDC ("finger joint") with an increasing

depth of girder also tensile stressing in addition to the bending stress and strain is occurring.
With a layer thickness of 32 mm, the KDC is quasi being stressed only just by tension as from a girder depth of 608 mm (see Figure 7).
This would be an explanation of the phenomenon why the dovetail ("finger") tensile strength becomes decisive and the "depth factor" is being eliminated beyond $h = 608$ mm.

Addition tests and investigations for the failure type A within the range of $h = 608$ mm are still required in order to provide for a final statement. The available small number of random samples does not yet permit to come to a conclusion.

6. "Depth dependence" modification factor k_h for glued laminated timber ("depth factor")

With a view to determining the modification factor k_h, the mean values of the bending strength $f_{m,mean}$ of "BSH 0"-type glued laminated timber are being applied (see Figure 8).
The experimental depth factor is being calculated according to Figure 9 (equation (1)) for the failure types A and B subject to the volume ratio V / V_1 and the depth ratio h / h_1 and is being entered for the failure type B into the Figures 11 and 12. In this connection, the volume amounts to $V = b \cdot h \cdot l_1$ (with l_1 being the effective span).

The regression analysis results in very small correlation coefficients r (see Figure 10) for the failure type A.

This means that there doesn't exist any depth dependence for the failure type A.

As for failure type B, significant correlation coefficients are existing (see Figure 10, equations (8) to (11)).

They are verifying the depth dependence of the bending strength for the heavily stressed zone being free from KDC ("finger joints") (failure type B).

The obtained regression equations with the highest correlation coefficients r from (8) and (9) are being entered into the Figures 11 and 12.

Furthermore, the theoretical depth factor $k_{h,theor.}$ is being calculated according to Colling /7/ for the failure type B subject to the volume ratio according to Figure 9 (2) and (3) and is being entered into Figure 11. One can see that the theoretical depth factor curve is developing below the k_h depth factor curve being determined as a result of the test values.

A comparison of the depth factor determined from the test values with the k_h-value according to the Eurocode 5 /8/, Annex 2, page 110

$$k_h = \left(\frac{200}{h}\right)^{0.2} = \frac{1}{\left(\frac{h}{200}\right)^{0.2}} \qquad (12)$$

results - with equal depth ratios h / h_1 - almost in a conformity (see Figure 12).

7. Summary

The evaluation of the bibliography (publications) and our own specific tests and investigations performed by means of glued laminated timber girders are demonstrating that for the failure type A (KDC ("finger joint") failure within the stressed zone) there doesn't exist any interrelation between the girder depth and bending strength.

As for the failure type B (knot or timber failure within the heavily stressed zone), a statistically covered and verified interrelation between the stressed volume or girder depth and the bending strength can be determined.

The tests are verifying the depth factor as indicated in the Eurocode 5 for the failure type B.

8. Bibliographical references

/1/ J. Ehlbeck, F. Colling:
"Die Biegefestigkeit von Brettschichtholzträgern in Abhängigkeit von den Eigenschaften der Brettlamellen"
(The bending strength of glued laminated timber girders subject to the properties of the board lamellae)
Published in: Bauen mit Holz, No. 10/87, pp. 646 - 655.

/2/ J. Ehlbeck, F. Colling:
"The strength of glued laminated timber (GLULAM) - Influence of lamination qualities and strength of timber joints"
CIB W 18, 2 1-12-3; Canada, September 1988.

/3/ W. Schöne:
"Der Einfluß der Trägerhöhe auf die Biegefestigkeit von Brettschichtholz"
(The influence of the girder depth on the bending strength of glued laminated timber)
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/4/ GDR Industrial Code Specification TGL 33 135/03 E 88:
"Holzbau - Tragwerke; Gütebedingungen für Bauschnittholz"
(Timber construction - Loadbearing structures; Quality specifications for sawn structural timber)
Draft, March 1988.

/5/ R. Apitz:
"Ermittlung von Festigkeitskennwerten für Vollholz bei der Beanspruchung Biegung durch Versuche"
(Determination of strength characteristics for solid timber subjected to bending stress by tests)
Wismar Engineering College; Progress report dated 1982-11-27.

/6/ B. John:
"Statistische Verfahren für technische Meßreihen"
(Statistical methods for technical series of measurements)
Published by: Carl Hauser Verlag, Munich/Vienna, 1979.

/7/ F. Colling:
"Einfluß des Volumens und der Spannungsverteilung auf die Festigkeit eines Rechteckträgers"
(Influence of the volume and of the stress distribution on the strength of a rectangular girder)
Published in: Holz als Roh- und Werkstoff, No. 44 (1986) 4, pp. 121 - 125, and No. 44 (1986) 5, pp. 179 - 183.

/8/ Eurocode 5:
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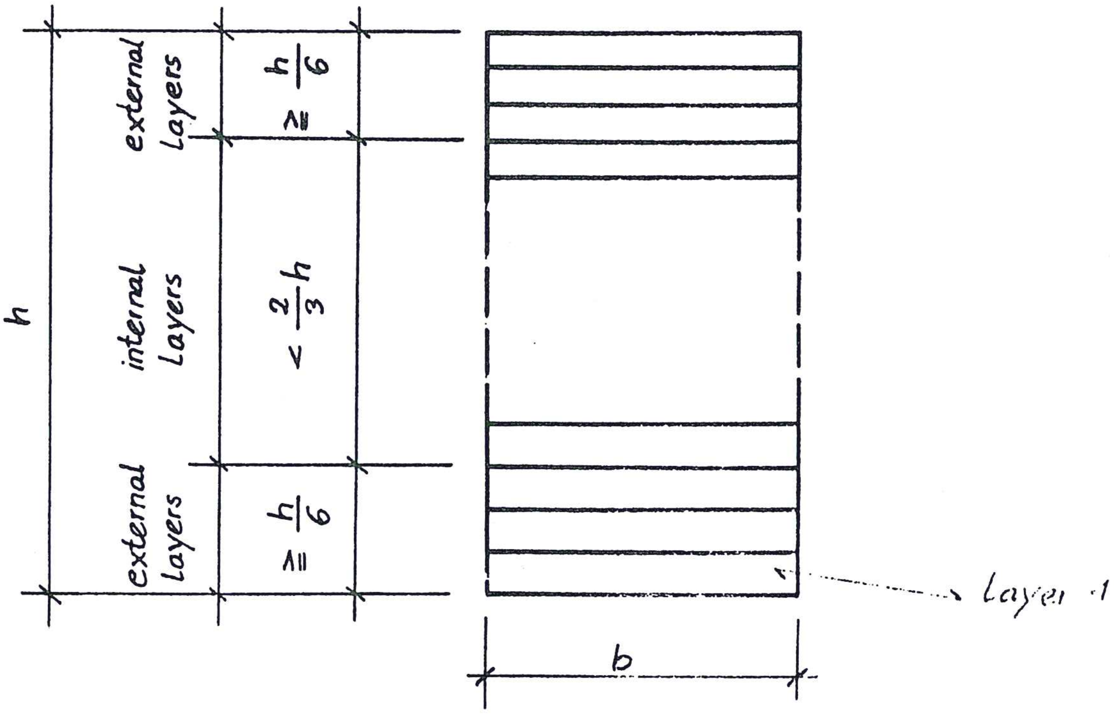
Deutsche Entwurfsfassung (German draft wording)
October 1987

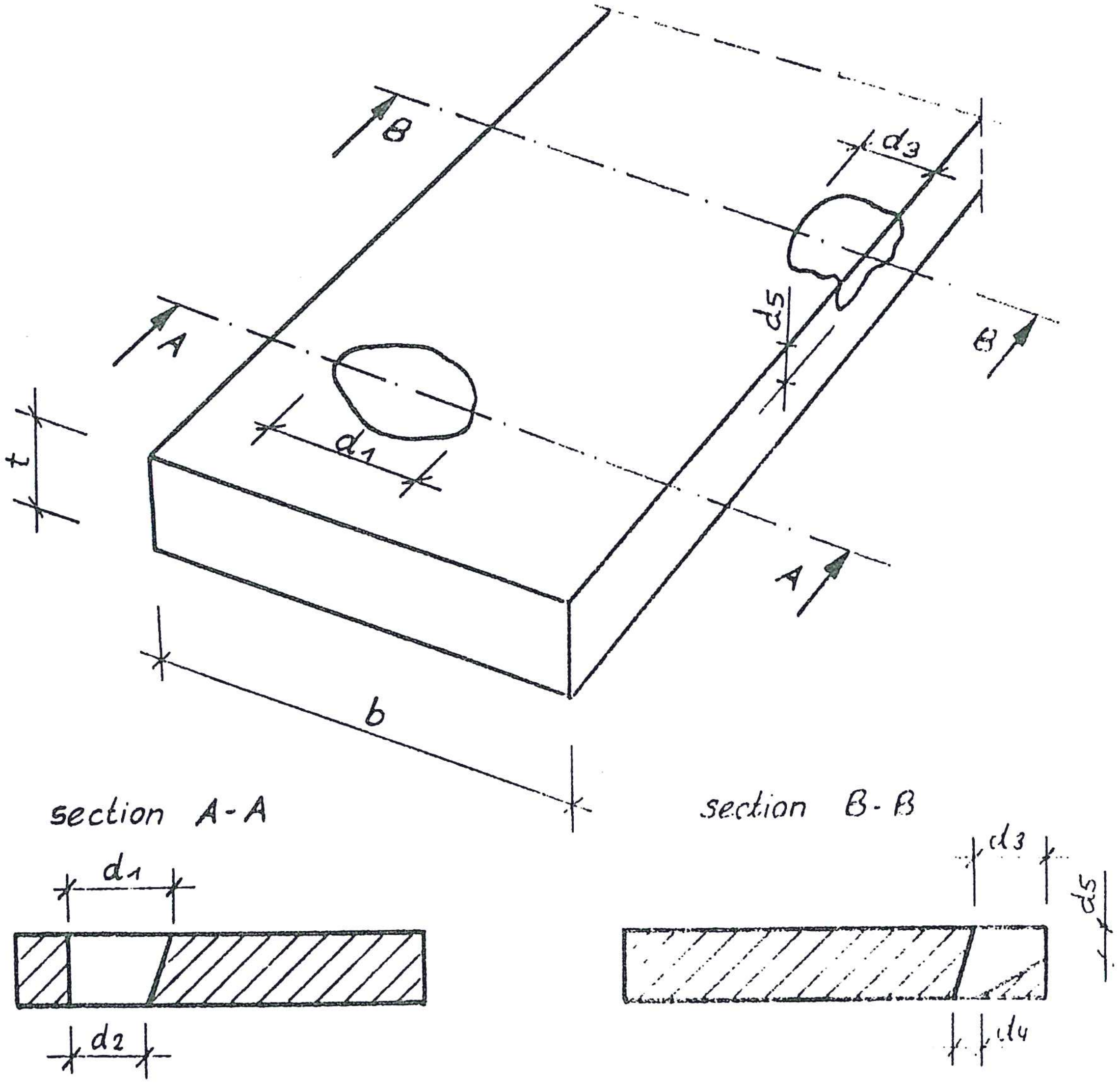


grade		BSH 0	BSH M3
sorting of the layers		visually	mechanically
external layers	kind of timber	NSH GK II	NSH F II
	KZV (mm)	≧ 250	≧ 250
internal layers	kind of timber	NSH GK II	NSH F III
	KZV (mm)	≧ 0	≧ 0

Meanings:

BSH = glued laminated timber
NSH = sawn coniferous timber
KZV = Key-dovetail connection ("finger joint") staggering
Gk = quality class
F = strength class

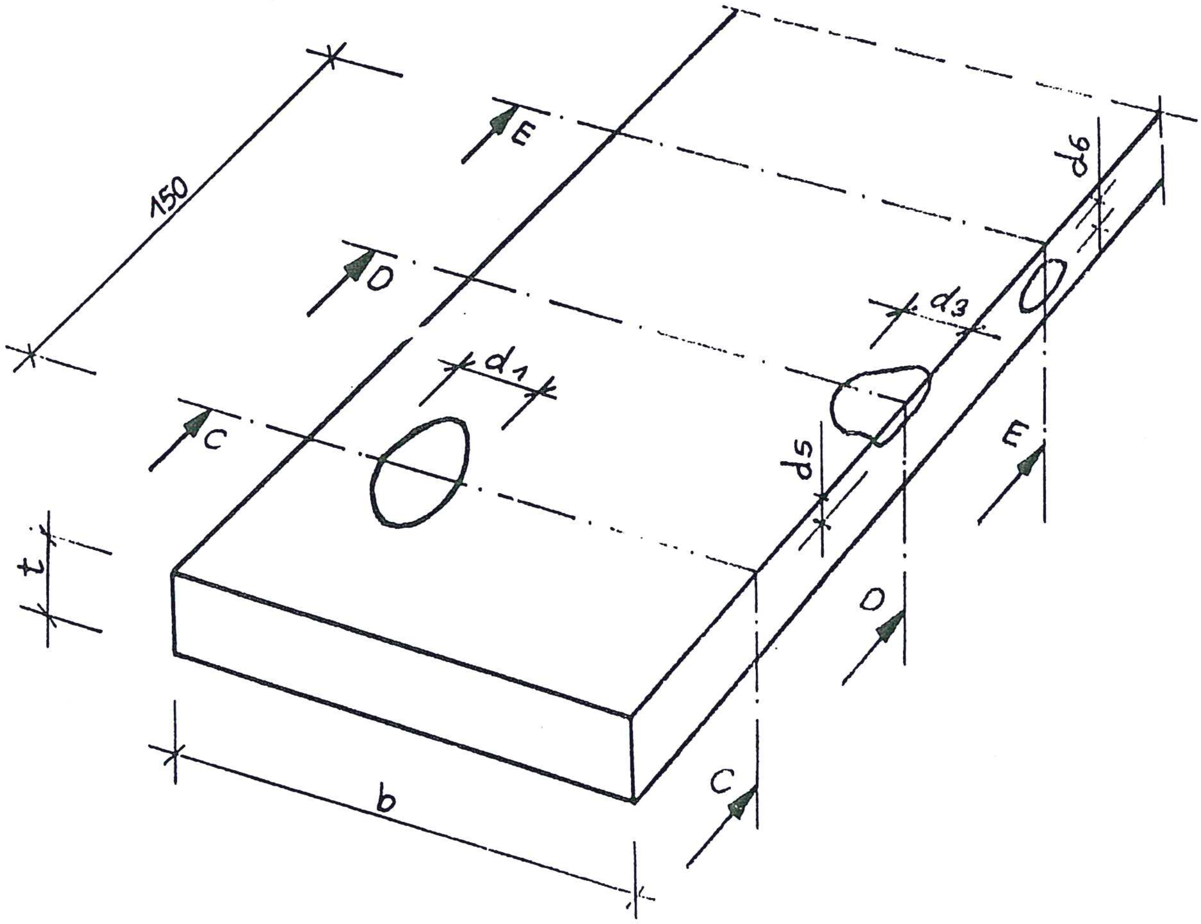
Figure 1: Grades of glued laminated timber



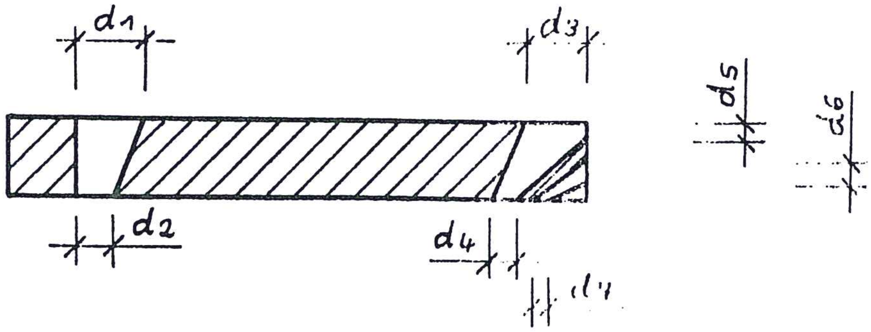
$$K = \frac{d_1 + d_2}{2b} \quad ; \quad \frac{d_3 + d_4 + d_5}{2b}$$

	quality class	strength class
$\leq \frac{1}{3}$	GK II	F II
$\leq \frac{1}{2}$	GK III	F III

Figure 2: Sorting by individual knots



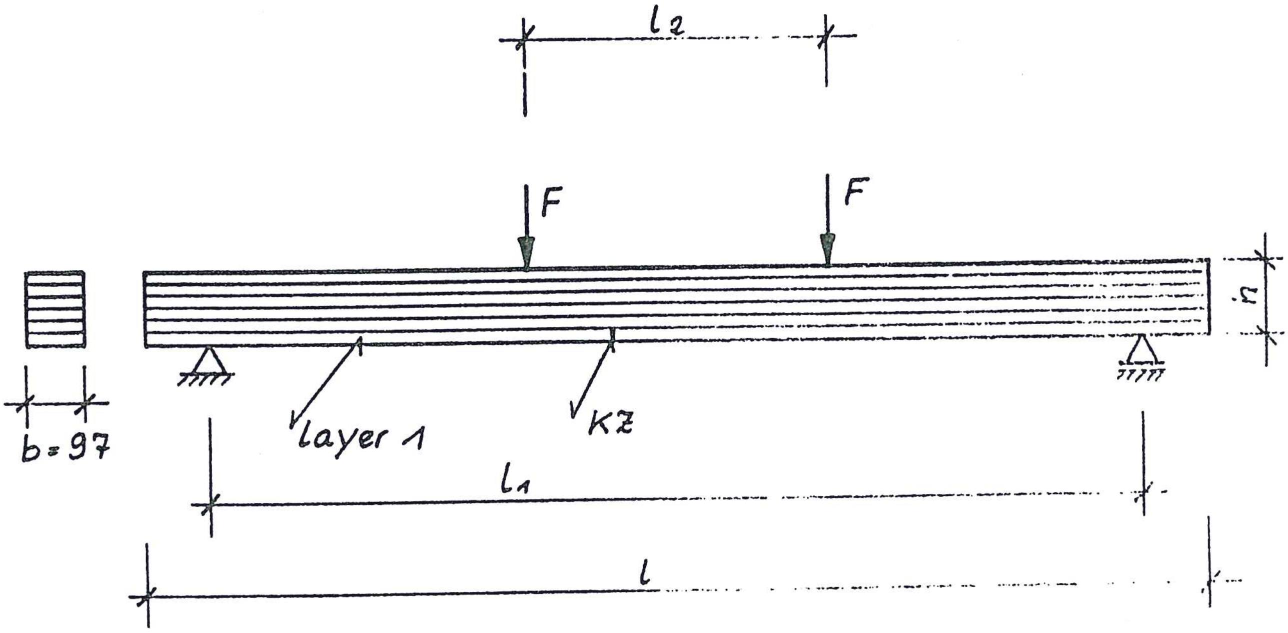
sections C-C, D-D, E-E in one sectional drawing



$$K = \frac{d_1 + d_2 + d_3 + d_4 + d_5 + d_6 + d_7}{2b}$$

K	quality class	strength class
≤ 1/2	GK II	F II
≤ 2/3	GK III	F III

Figure 3: Sorting by accumulations of knots



Meanings:

h = test specimen height

l = test specimen length

l_1 = effective span, $l_1 = 15\,h$

l_2 = test zone length, $l_2 = 4\,h$

KZ = Key - dovetailing ("finger joint"), always located within the test zone l_2, layer 1

Figure 4: Test arrangement

test No.	h mm	l_1 mm	l_2 mm	n –	$E_{m,mean}$ $\frac{N}{mm^2}$	$f_{m,mean}$ $\frac{N}{mm^2}$	s $\frac{N}{mm^2}$	k –	$f_{m,k}$ $\frac{N}{mm^2}$	tensile failure within the test zone l_2, failure type:
1	288	4320	1152	5	11830	38,0	1,93	2,26	33,6	KDC ("finger joint")
2				28	11214	45,0	5,73	1,645	35,6	Knot or timber
3	608	9120	2432	7	12014	36,0	4,12	2,13	27,2	KDC ("finger joint")
4				5	11200	36,6	4,51	2,26	26,4	Knot or timber
5	800	12000	3200	8	13663	37,4	6,26	2,09	24,3	KDC ("finger joint")
6				3	13267	38,7	3,06	2,61	30,7	Knot or timber
7	992	14880	3968	5	13700	39,1	5,35	2,26	27,0	KDC ("finger joint")
8				5	12960	36,9	4,75	2,26	26,2	Knot or timber

$b = 97$ mm

Meanings:

n = number of test specimens
$E_{m,mean}$ = mean value of the modulus of elasticity in bending
$f_{m,mean}$ = mean value of the bending strength

s = standard deviation
k = factor of conversion from small to large random sample numbers
$f_{m,k}$ = characteristic value of the bending strength (5%-quantile)

Figure 5: Test results of "BSH 0"-type glued laminated timber girders subjected to bending

test No.	h mm	l_1 mm	l_2 mm	n -	$E_{m,mean}$ $\frac{N}{mm^2}$	$f_{m,mean}$ $\frac{N}{mm^2}$	s $\frac{N}{mm^2}$	K -	$f_{m,K}$ $\frac{N}{mm^2}$	tensile failure within the test zone l_2, failure type :
1	192	2880	768	12	10 909	33,3	5,27	1,99	22,8	KDC ("finger joint")
2				12	11683	42,3	10,8	1,99	20,8	Knot or timber
3	288	4320	1152	7	12 417	37,1	5,52	2,13	25,3	KDC ("finger joint")
4				5	12 070	37,4	8,06	2,26	19,2	Knot or timber
5	608	9120	2432	10	12851	35,8	5,59	2,03	24,5	KDC ("finger joint")
6				-	-	-	-	-	-	Knot or timber

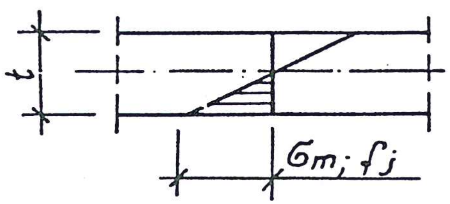
$b = 97$ mm

h = test specimen height
l_1 = effective span
l_2 = test zone length
n = number of test specimens

$E_{m,mean}$ = mean value of the modulus of elasticity in bending
$f_{m,mean}$ = mean value of the bending strength
s = standard deviation
k = factor of conversion from small to large random sample numbers
$f_{m,k}$ = characteristic value of the bending strength (5% - quantile)

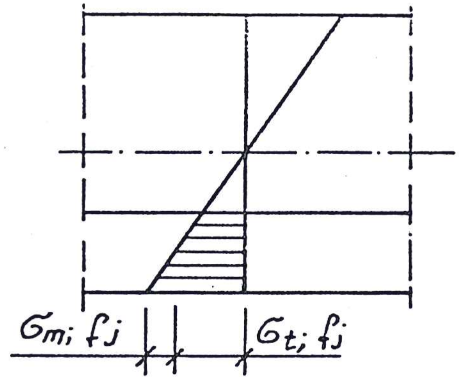
Figure 6 : Test results of "BSH M 3" - type glued laminated timber girders subjected to bending

a) pure bending within the KDC ("finger joint")



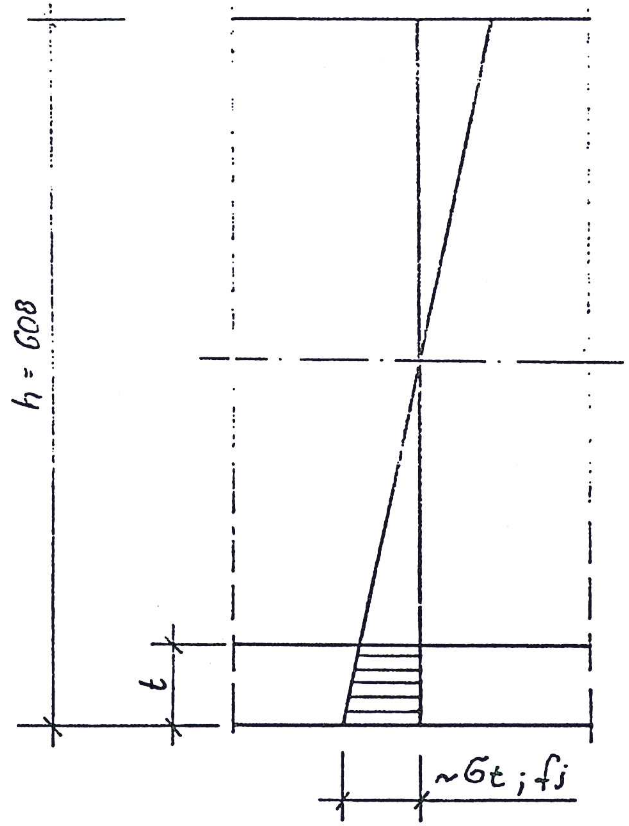
$\sigma_m; f_j = f_{m,k}; f_j$

b) bending and tension within the KDC



$f_{t,0,k}; f_j < \sigma_m; f_j + \sigma_t; f_j < f_{m,k}; f_j$

c) quasi-tension within the KDC



$\sigma_t; f_j = f_{t,0,k}; f_j$

Meanings:

σf_j = stress within the KDC
$f_k; f_j$ = charakteristic strength of the KDC (5%-quantile)
KDC = key-dovetail connection ("finger joint")

Figure 7: Stressing of the key-dovetail connection ("finger joint") with increasing depth of a glued laminated timber girder

i	h	l_1	l_2	$V_i = b \cdot h \cdot l_1$	n	$f_{m,mean}$	k_h, exp. (1)	failure type	λ_L (2)	$\frac{\lambda_{L,1}}{\lambda_{L,i}}$	$\frac{V_i}{V_1}$	$\frac{h_i}{h_1}$	k_h, theor. (3)
	mm	mm	mm	m^3	–	$\frac{N}{mm^2}$	–		–	–	–	–	
1	288	4320	1152	0,121	5 28	38,0 45,0	1 1	A B	– 2,38	– 1	1	1	– 1
2	608	6080	2432	0,359	1 4	40 44,1	1,053 0,98	A B	– 2,61	– 0,912	2,97	2,11	– 0,796
3	608	9120	2432	0,538	3 3	33,2 34,0	0,874 0,756	A B	– 2,61	– 0,912	4,45	2,11	– 0,757
4	608	12160	2432	0,717	4 2	38,1 40,5	1,003 0,9	A B	– 2,61	– 0,912	5,93	2,11	– 0,730
5	800	8000	3200	0,621	6	37,5 –	0,987 –	A B	– 2,70	– 0,881	5,13	2,78	– 0,718
6	800	12000	3200	0,931	4 1	33,8 36	0,889 0,8	A B	– 2,70	– 0,881	7,69	2,78	– 0,683
7	800	16000	3200	1,242	4 2	41,0 40,0	1,079 0,889	A B	– 2,70	– 0,881	10,26	2,78	– 0,659
8	929	9290	3716	0,837	6	36,0 –	0,947 –	A B	– 2,75	– 0,865	6,92	3,23	– 0,679
9	992	14880	3968	1,432	3 3	40,2 38,7	1,058 0,86	A B	– 2,78	– 0,856	11,83	3,44	– 0,629
10	992	19840	3968	1,909	3 2	35,8 34,3	0,942 0,762	A B	– 2,78	– 0,856	15,78	3,44	– 0,606

$b = 97$ mm

Figure 8: Mean value of the bending strength $f_{m,mean}$ and modification factor k_h of "BSH 0"-type glued laminated timber

$$k_{h,exp} = \frac{f_{m,mean,i}}{f_{m,mean,1}} \qquad (1)$$

According to /7/, the result is

$$\lambda_L = \left[\frac{1}{m+1} \cdot (1 + l_2\, m)\right]^{\frac{1}{m}}$$

m Weibull's exponent, depending on the variation coefficient of the corresponding type of stressing , m = 8

$$\lambda_L = \left[\frac{1}{9} \cdot (1 + 8\, l_2)\right]^{0,125} \qquad (2)$$

λ_L = solidity ratio in the direction of l_1

According to /7/, the result is

$$k_{h,theor.} = \frac{\lambda_{L,1}}{\lambda_{L,i}} \cdot \frac{\lambda_{h,1}}{\lambda_{h,i}} \left(\frac{V_1}{V_i}\right)^{\frac{1}{m}}$$

$$\lambda_h = \left(\frac{1}{m+1}\right)^{\frac{1}{m}}$$

λh solidity ratio in the direction of h

The result for an equal m is $\lambda_{h,i} = \lambda_{h,1}$

and thus

$$k_{h,theor.} = \frac{\lambda_{L,1}}{\lambda_{L,i}} \cdot \left(\frac{V_i}{V_1}\right)^{-\frac{1}{m}}$$

With m = 8, the result is

$$k_{h,theor.} = \frac{\lambda_{L,1}}{\lambda_{L,i}} \left(\frac{V_i}{V_1}\right)^{-0,125} \qquad (3)$$

Figure 9: Calculation of $k_{h,exp}$ and $k_{h,theor.}$

failure type A

$$k_h = 0{,}9863 \cdot \left(\frac{V}{0{,}121}\right)^{-0{,}0031} \quad ; \quad V \text{ in } m^3 \qquad (4)$$

$r = 0{,}034$

$$K_h = 0{,}9899 \left(\frac{h}{288}\right)^{-0{,}0033} \quad ; \quad h \text{ in mm} \qquad (5)$$

$r = 0{,}048$

$$k_h = 0{,}9764 \quad e^{0{,}00065 \left(\frac{V}{0{,}121}\right)} \qquad (6)$$

$r = 0{,}040$

$$K_h = 0{,}9868 \quad e^{-0{,}0023 \left(\frac{h}{288}\right)} \qquad (7)$$

$r = 0{,}024$

failure type B

$$K_h = 0{,}993 \cdot \left(\frac{V}{0{,}121}\right)^{-0{,}0796} \quad ; \quad V \text{ in } m^3 \qquad (8)$$

$r = 0{,}664$

$$K_h = 0{,}996 \left(\frac{h}{288}\right)^{-0{,}1677} \quad ; \quad h \text{ in mm} \qquad (9)$$

$r = 0{,}628$

$$K_h = 0{,}9512 \; e^{-0{,}0128 \left(\frac{V}{0{,}121}\right)} \qquad (10)$$

$r = 0{,}593$

$$K_h = 1{,}052 \cdot e^{-0{,}0796 \left(\frac{h}{288}\right)} \qquad (11)$$

$r = 0{,}608$

Figure 10: Regression analysis for "BSH 0" - type glued laminated timber

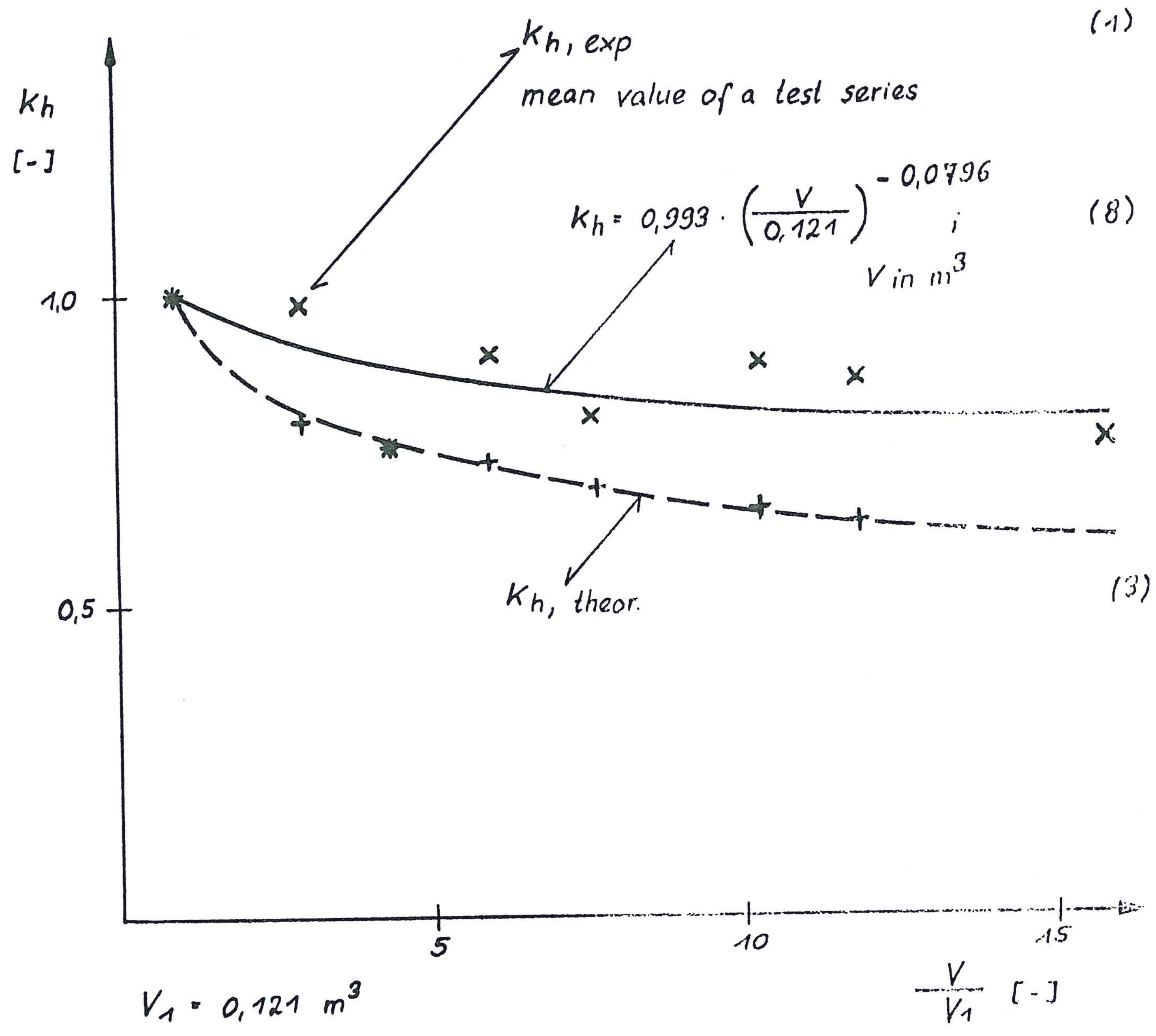
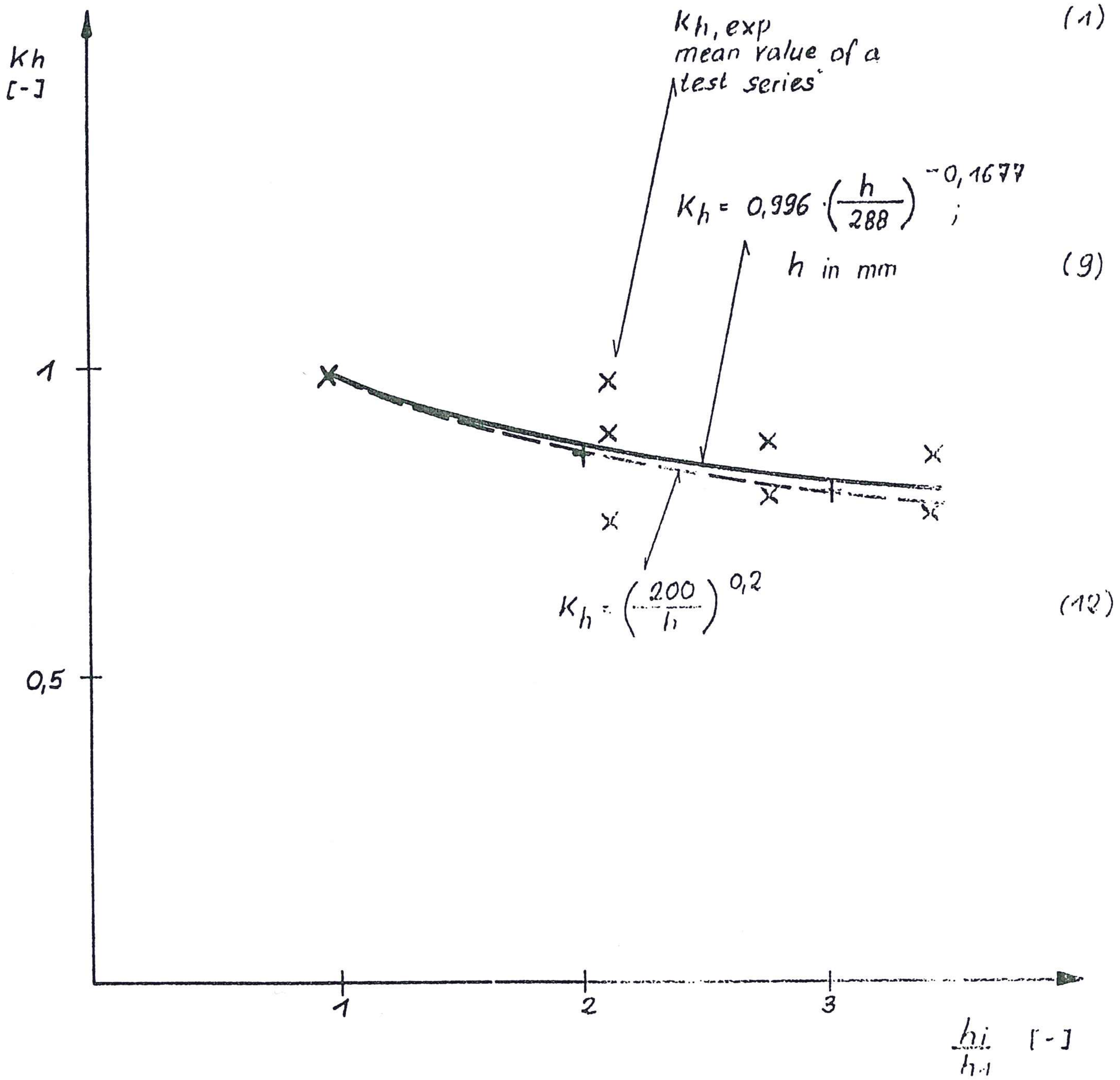


Figure 11: Modification factor k_h subject to the volume ratio for failure type B (BSH 0)



h_1 = 288 mm with (1) and (9)

h_1 = 200 mm with (12)

Figure 12: Modification factor k_h subject to the cross-sectional height for failure type B (BSH 0)

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