A STUDY ON TENSION STRENGTH OF FINGER JOINTS IN BEECH WOOD LAMINATIONS

EINE STUDIE ZUR ZUGFESTIGKEIT VON KEILZINKENVERBINDUNGEN IN BRETTLAMELLEN AUS BUCHENHOLZ

UNE ÉTUDE SUR LA RÉSISTANCE EN TRACTION DU JOINT D'ABOUTAGES EN BOIS DE HÊTRE

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SUMMARY

Beech wood, a timber species with high strength and stiffness properties, is today almost exclusively used in non-structural applications. The potential use of beech for load bearing construction purposes and hereby for glued laminated timber, due to several reasons, has recently gained considerably increased importance for German forestry. This trend will be enhanced in future due to considerable shifts in afforestation policies in several districts towards increased stands of beech trees.

This paper reports on some results of a pilot study on finger joint tension strength and respective density and stiffness correlations of beech wood laminations. The longitudinal stiffness of the laminations, cut from six different trees, were determined by two methods, being ultra-sound wave velocity and elongation measurements in tension tests. The results of both methods were highly correlated. Partly, extreme differences in stiffness/density correlations between different trees were obtained.

Excluding laminations of two stems with high fiber deviation a mean finger joint tension strength of 70 ± 11 N/mm2 was obtained. The entity of all joints of the pilot study gave a coefficient of correlation of $R = 0{,}67$ between finger joint tension strength and longitudinal tension modulus of elasticity of the less stiff adherent. The tests revealed the high strength relevancy of fiber deviation of the adherents in the joint line, which is very hard to detect in a visual grading process at this particular timber species.

ZUSAMMENFASSUNG

Buchenholz, eine Holzart mit hohen Festigkeits- und Steifigkeitseigenschaften, wird heute nahezu ausschließlich für nichttragende Zwecke eingesetzt. Die potenzielle Nutzung von Buche für tragende Verwendungen im Bauwesen und hierbei für Brettschichtholz hat in jüngerer Zeit aus mehreren Gründen erhöhte Bedeutung für den deutschen Forst erfahren. Dieser Trend wird sich in Zukunft infolge beträchtlicher Verschiebungen in der Aufforstungspolitik hin zu größeren Buchenbeständen noch verstärken.

Dieser Aufsatz berichtet über einige Ergebnisse einer Pilotstudie zur Zugfestigkeit und diesbezügliche Dichte- und Steifigkeitskorrelationen von Keilzinkenverbindungen mit Buchenlamellen. Die Längssteifigkeiten der Lamellen, die aus sechs verschiedenen Stämmen geschnitten waren, wurden mit den beiden Methoden – Ultraschall-Wellengeschwindigkeit und Längenänderungsmessung im Zugversuch – bestimmt. Die Ergebnisse beider Methoden waren hoch korreliert. Zum Teil wurden extreme Unterschiede in den Steifigkeits- Dichtekorrelationen zwischen unterschiedlichen Stämmen erhalten.

Bei Ausschluss von Brettlamellen zweier Stämme, die eine hohe Faserabweichung aufwiesen, wurde eine mittlere Keilzinkenzugfestigkeit von 70 ± 11 N/mm2 erhalten. Die Gesamtheit aller Keilzinkenverbindungen der Pilotstudie ergab einen Korrelationskoeffizienten von $R = 0{,}67$ für den Zusammenhang der Keilzinkenzugfestigkeit mit dem Zugelastizitätsmodul in Lamellenlängsrichtung des schwächeren Fügeteils. Die Versuche zeigten die hohe Festigkeitsrelevanz von Faserabweichungen der Fügeteile auf, die jedoch bei dieser speziellen Holzart äußerst schwer im Rahmen eines visuellen Sortierprozesses bestimmbar sind.

RESUME

Le bois de hêtre, une essence présentant de fortes caractéristiques de rigidité et de résistance, est aujourd'hui presque exclusivement utilisé dans des applications non structurales. La valorisation potentielle de ce bois comme matériau de structure et notamment sous forme de poutres lamellées collées, a récemment suscité un intérêt considérablement accru de la part de l'industrie forestière allemande. Cette tendance s'accentuera dans le futur du fait de réorientations considérables des politiques forestières de plusieurs districts vers une utilisation accrue du hêtre en plantation.

Cet article fait état des résultats d'une étude pilote sur la résistance en traction d'aboutages en bois de hêtre, et la corrélation entre densité et rigidité des lamelles aboutées. Les rigidités axiales des lamelles, prélevées sur 6 arbres différents, ont été déterminées par deux méthodes, la vitesse de propagation ultrasonore et la mesure de l'élongation lors des essais de traction. Les résultats des deux méthodes étaient fortement corrélés. Des différences inter arbre extrêmement significatives pour la corrélation module/densité ont été observées. En excluant les lamelles de deux tiges présentant une déviation importante des fibres, une valeur moyenne de 70 ±11 N/mm² a été obtenue pour la résistance en traction des aboutages. L'analyse de l'ensemble des résultats d'essais de cette étude pilote a fait apparaître un coefficient de corrélation R= 0,67 entre la résistance en traction du joint d'aboutage et le module d'élasticité axial le plus faible parmi les deux lames aboutées. Les essais ont révélé l'importance de la déviation des fibres au niveau du joint sur sa résistance, paramètre qu'il est très difficile de détecter par classement visuel pour cette essence.

KEYWORDS: beech wood laminations, MOE determination with ultra-sound wave velocity, density/stiffness correlations, finger joint tension strength, stiffness/strength correlations

1. INTRODUCTION

In today's timber construction in the Northern hemisphere the use of softwoods is by far dominating. Glued laminated timber, apart from a very few exceptions, is almost entirely made from softwood laminations. The reasons for the neglect of hardwoods, being extensively used timber construction materials in former centuries, despite high strength and stiffness potential, are manifold. However, recently, the potential use of beech wood, today almost entirely used in non-structural applications, as a valuable timber species for construction purposes and hereby for glued laminated timber has gained increased importance for German forestry. The reason therefore are increasing amounts of small and large diameter stems, which due to knots and/or red stain formation, the latter typical for beech wood, can not be marketed for the furniture and veneer industry. This pressure to seek for new marketing areas will increase in future due to considerable shifts in afforestation policies leading to a considerably higher percentage of beech in many forest areas, especially in Baden-Württemberg. The change in planting policy is a result of the extensive forest damages due to hurricanes experienced in the last decade, delivering evidence that spruce/fir monocultures are strongly volatile at inapt soils. At these stands, beech as the natural growing species, performs far better.

The performed pilot study aimed at several aspects, being material property determination of structural sized beech wood in general, specific species bound grading aspects and NDT determination of longitudinal modulus of elasticity. A special interest focussed on a realistic assessment of finger joint tension strength and respective scatter of joints manufactured in industrial conditions.

This paper reports on some aspects of the employed tree/lamination source, on stiffness vs. density correlations of the laminations and on finger joint tension test results.

2. LITERATURE REVIEW

A first comprehensive experimental study on bending and tension strength of beech wood lumber and boards and correlations with grading parameters was performed by Glos and Lederer (2000). It should be stated that the timber used in the cited study obviously showed different knot sizes and distributions as the raw material investigated in this study. That difference is related to a different source of the timber and to different positions of the respective log segments in the stems. Some details on this are given in chapter 3.

Concerning strength of finger joints and of glulam beams with beech wood laminations, a few qualitative indications on the strength potential were published by Gehri (1985). The data, unfortunately not published in correlation with any grading or density characteristics of the timber material, suggest that finger joint tension strength values are in the range of 80 – 100 N/mm2. The minimum glulam bending strength of four glulam beams with depths > 500 mm was found larger than 50 N/mm2.

3. TIMBER MATERIAL

The laminations investigated were cut from six (5 ½) stem segments, here denoted by A to F, of beech wood trees. The diameters of the stems varied from 45 to 57 cm, the lengths of the stem segments ranged from 2,3 to 2,9 m. The employed stem segments conformed to so-called “forest stem classes” A and B, characterized i.a. by diameters > 30 cm resp. 20 cm, and which in general are cut from the lower stem part.[1] The stems were already sawn in planks with the sawing pattern shown in Figs. 1a, b. The depicted sawing scheme is the widely prevailing one for beech wood today in Europe. The planks had been air-dried to moisture contents varying between and within the different stems in the range of 12,5 to 15,7 %. Air-drying at outdoor conditions between 6 to 12 months is usual for beech wood boards. This procedure is due to the fact that kiln drying of beech material is far more problematic as in case of softwoods as the high shrinkage anisotropy and other specific growth characteristics of beech wood result in a strong tendency to cracking and warping, what is especially pronounced in the vicinity of the pith[2].

Without discussing in detail grading aspects and defect classifications, a general statement as following can be made: The knot sizes and distributions and the associated fiber deviations in the investigated timber material were more different from softwood than anticipated. For the specifically investigated stem/plank batch, the situation concerning knots can be specified qualitatively as following:

In case of a knot, the defect was in most cases so large that the absolute knot size resp. the knot area ratio of all perceivable board widths, also restricted by the fissures and cracks, was beyond acceptable/sensible ratios for boards (here: glulam lamellas) classified according to the second lowest visual hardwood grade, S10, according to draft standard E DIN 4074- 5, for hardwood grading.

The planks were cut and planed in the institute's workshop to laminations free of defects (with diameters $>$ 5 mm) with cross-sectional dimensions (b x d) of 120 x 46 mm with lengths varying from 950 to 2500 mm.

It is important to state that the boards were not graded with respect to fiber deviations, although required by E DIN 4074-5, as determination of fiber deviations contrary to softwoods is extremely problematic in case of beech. Further aspects of fiber deviation are discussed in chapter 7.

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[1] Contrary to the here investigated beech timber, the planks used by Glos and Lederer (2000) were of considerably smaller diameters. The stems were either harvested in thinning operations or were cut from tree positions in the upper part (so-called 2nd and 3rd length) with higher knot density.

[2] According to draft visual grading rules for beech wood (E DIN 4074-5) pith and partial pith affected areas are excluded for structural boards.

Fig. 1: View of employed beech stem segments and respective sawing pattern
a) stem A
b) stem B

The longer boards were than subdivided into lengths of about 950 and 1800 mm. The lamination (segment) length of about 950 mm conformed to the smallest length which could be handled in the industrial finger jointing process in the glulam company manufacturing the finger joints. The longer boards were used for complementary tests without joints. The final length of the laminations used for finger jointing was 900 mm.

4. DETERMINATION OF LONGITUDINAL MODULUS OF ELASTICITY

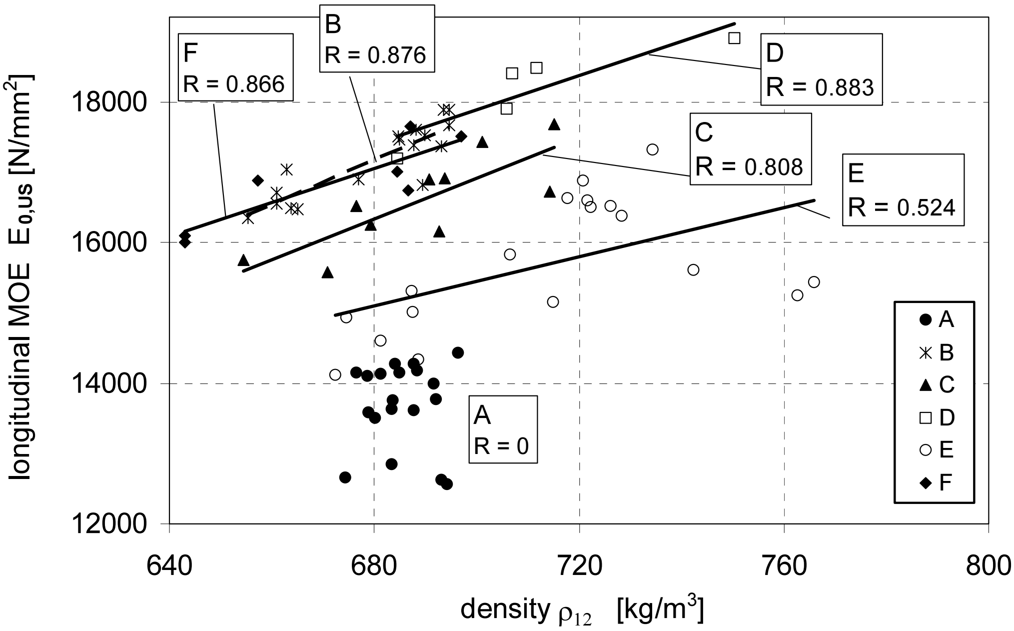
It was assumed that density of the quasi defect free material is not sufficiently correlated with longitudinal stiffness and strength of the laminations. So, for assessment of stiffness and strength (differences) of the laminations of the different stems, modulus of elasticity $E_{0,US}$ in longitudinal, i.e. fiber direction, of all laminations was determined by ultra-sound (US) wave velocity measurement. The MOE was derived elementary for each lamination according to $E_{0,US} = v^2\rho$ where v is wave velocity and $\rho = \rho_{12}$ is density of the total lamination at nominally 12 % moisture content.

Table 1: Compilation of annual ring widths, densities and moduli of elasticity parallel to fiber of the six stems; given are means and coefficients of variation.

stem	number of laminations	annual ring width		density ρ_{12}		modulus parallel to fiber from US-wave velocity $E_{0,US}$	
		mean	C.O.V.	mean	C.O.V.	mean	C.O.V.
-	-	mm	mm	kg/m^3	%	N/mm^2	%
A	20	5,1	0,7	683	1,4	13641	4,7
B	17	2,7	0,3	679	2,1	17155	3,1
C	10	2,2	0,4	689	2,8	16593	4,1
D	6	3,0	0,3	712	2,9	17904	5,0
E	22	3,7	0,7	714	3,6	15741	5,6
F	9	3,3	0,3	667	3,3	16660	4,1

Figures 2a,b depict separately for the laminations of each stem the obtained correlations between $E_{0,US}$ and density ρ_{12}. It is obvious from the graphs that the MOE vs. density trends and their respective correlations differ partly considerably between the six stems. Consequently, the coefficient of a linear MOE vs.

density regression for all laminations is almost zero (R = 0,19). However, laminations of stems B, D and F show well coinciding relationships. Further, in a rougher assessment, also laminations of stem C characterized by the same slope of $E_{0,US}$ vs. ρ, can be grouped to the B, D, F lamination batch.



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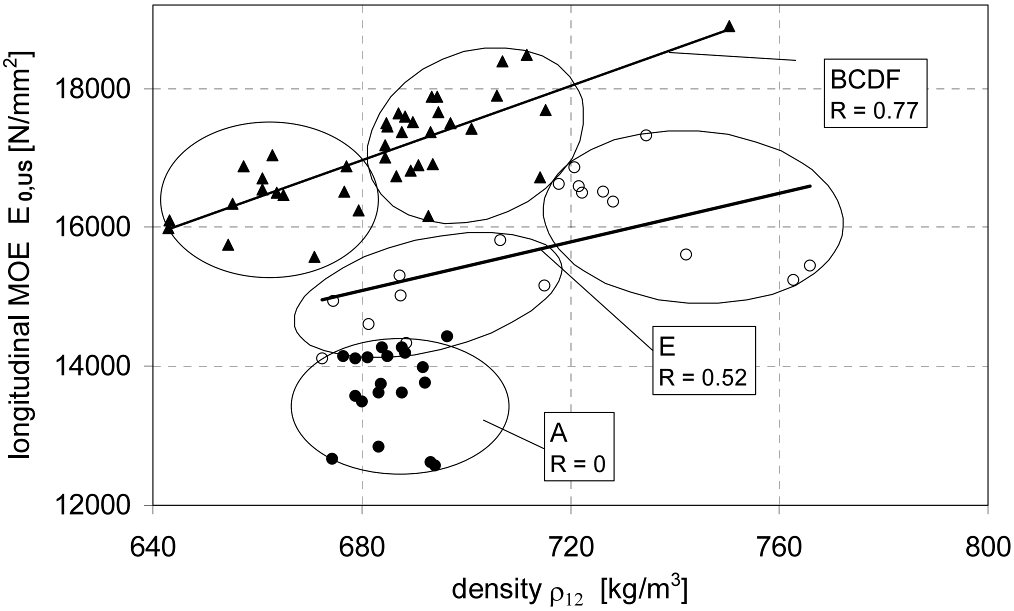


b)

Fig. 2: Correlation between longitudinal modulus of elasticity determined by ultra-sound wave velocity and density
a) of each of the six stems
b) of the three lamination batches BCDF, E and A. The circles indicate specimens of sub-batches which were jointed together.

Laminations of stem E and especially of stem A evidently differ rather resp. extremely from those of the other stems. Note, that stem A also differed from the other stems by a considerably larger annual ring width, which in average exceeded 5 mm; for the other stems the mean annual ring width varied from 2,2 to 3,7 mm (see Table 1).

In order not to produce finger joints obviously belonging to very different MOE ranges, assumingly correlated to strength, three different lamination batches were defined:

- *one* batch consisting of the laminations of stems B, C, D and F, following termed batch BCDF and *two* other batches consisting exclusively of the laminations of stems E and A, respectively.

Table 2: Compilation of finger joint collectives concerning density ranges of jointed laminations

batch (origin of lamellas from stems)	approx. density range of laminations kg/m^3	number of finger joint specimens [1)]
BCDF	640 to 680	8
	680 to 720	13
A	670 to 700	10
E	670 to 720	4
	720 to 770	7

[1)] The stated numbers of finger joints do not correspond exactly to the half of the laminations given in Fig. 2b; finally a few extra specimens from the longer laminations originally not intended for finger jointing were added.

Figure 2b shows the three lamination batches, their respective MOE vs. density regression lines, and the obtained coefficients of correlation which differ strongly for batches BCDF, A and E, emphasizing the statements made above.

As the laminations of batch BCDF and also of batch E still cover a rather large density and MOE range, both batches were subdivided into two sub-batches each, comprising the density ranges specified in Tab. 2. Within each sub-batch the laminations were finger-jointed randomly. The number of finger joints per batch varied from 4 to 13, which throughout are very small numbers, but this has to be seen in view of the pilot study approach.

5. MANUFACTURE OF THE FINGER JOINTS

The manufacture of the finger joints was performed under fully industrial conditions in a glulam company. The finger joints were manufactured with a single tact press; the joints were cut package-wise with four laminations at the time. The employed finger joint geometry (profile), being one of two most common geometries in Germany, showed the following dimensions: pith = 6 mm, tip width (nominal) = 1,2 mm and finger length (nominal) = 20 mm. Compared to finger jointing of softwood laminations, the end pressure had to be increased. The used adhesive was of Melamine type (liquid resin, liquid hardener) conforming to EN 301.

After production, the finger jointed laminations were conditioned for five months (due to non project bound reasons) in a climate chamber at 20°C/65% RH. Before testing, the joints were planed to final cross-sectional dimensions of 115 mm x 42 mm.

6. TEST PROCEDURE

The tests were performed in a servo-hydraulic tension test machine with special hydraulic grips for timber planks. The testing consisted of two successive campains. First, the longitudinal MOE's parallel to tension axis of both jointed laminations (adherents) were measured simultaneously with gauge lengths of tree times the lamination width with sufficient distance from the finger joint line and the clamping support. The test scheme is depicted in Fig. 3a. The elongations were measured by two LVDT's each, mounted diagonally opposite to both adherents. At the stiffness tests, serving essentially for correlations with MOE's determined with afore reported wave velocity measurements, the joints were ramp loaded to ranges of 15% to maximally 30% of the then unknown ultimate loads, using a constant cross-head speed of 0,04 mm/sec.

Immediately after stiffness testing, the grip lengths were increased to the necessary length to introduce the ultimate load (maximally 420 kN); the free length of the jointed laminations between the grips in the strength test was throughout four times the lamination width with the joint line at half length (Fig. 3b). The loading was performed in global displacement control with a constant cross-head speed of 0,04 mm/sec. After failure, the moisture content of the specimen was determined with a calibrated moisture meter suitable for beech wood. A further essential evaluation concerned the determination of the fiber deviation. The fiber deviation was measured in the failure area. A typical fiber deviation is depicted in Fig. 4b.

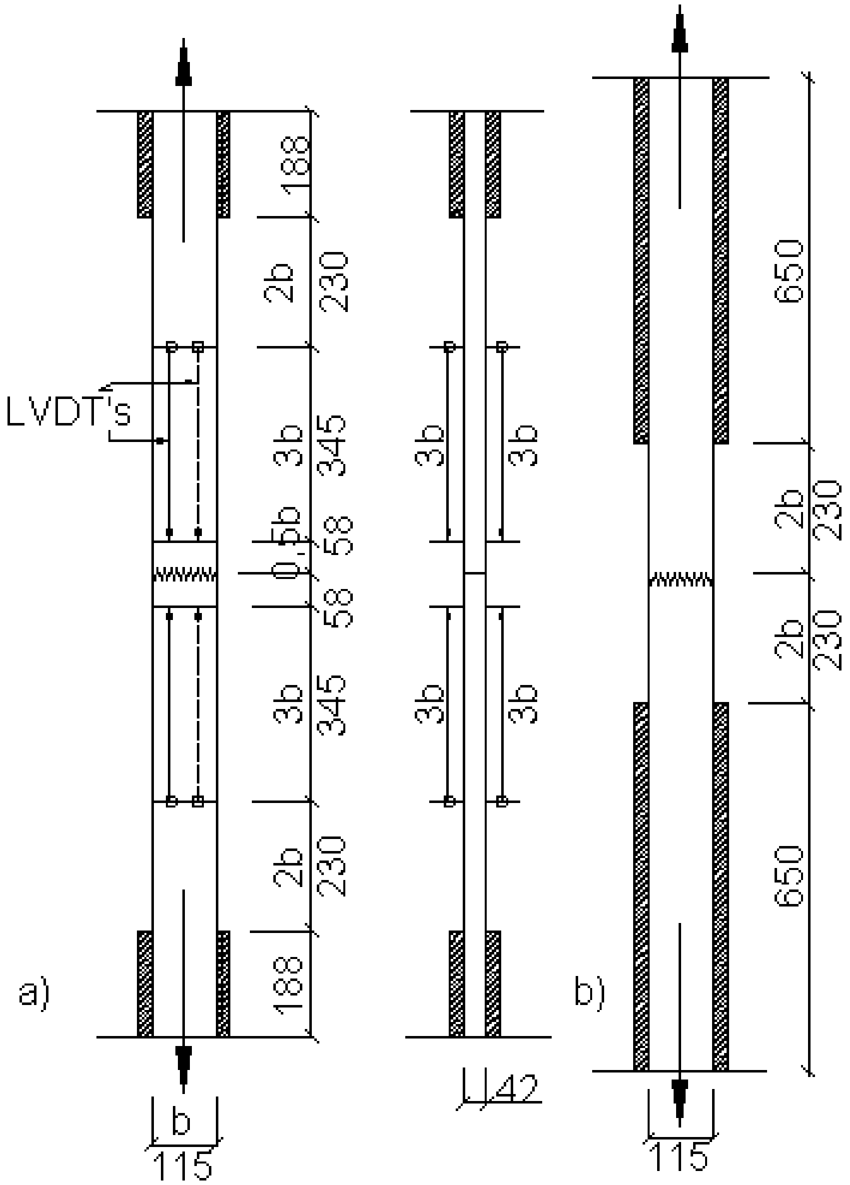
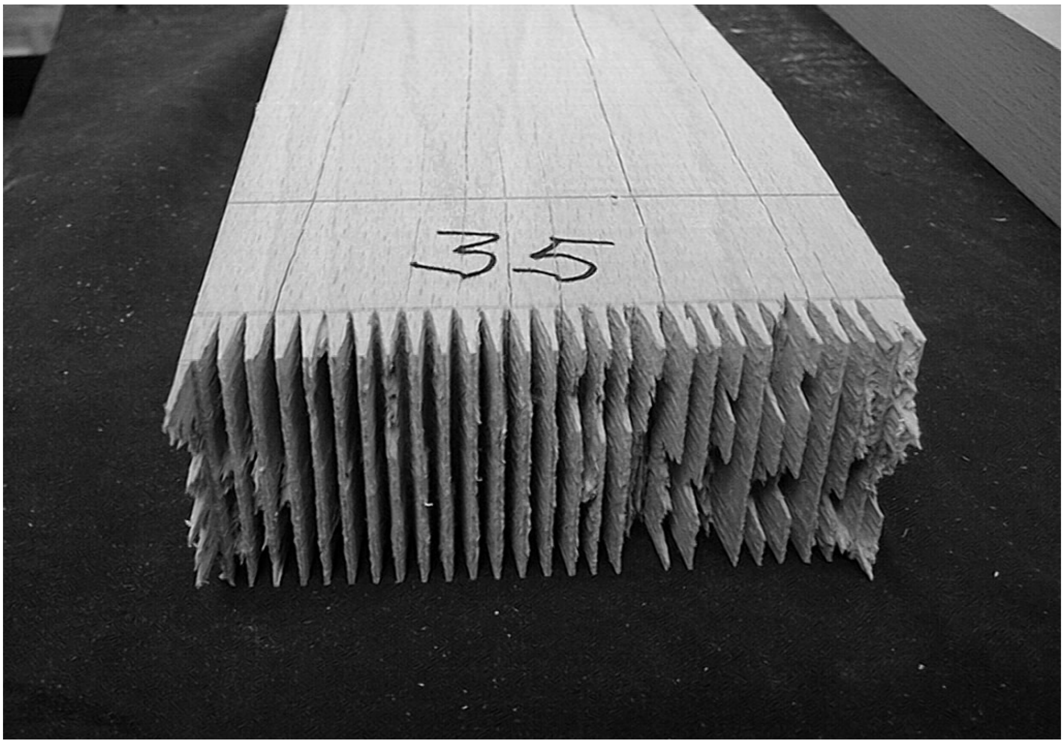


Fig. 3a, b: Views of test scheme

a) MOE determination of adherents in first loading

b) strength determination of the finger joint in second loading a)



b)

Fig. 4a, b: Views of finger joint tension failures
a) "pure" finger joint failure
b) "not pure" finger joint failure due to fiber deviation of one adherent with fiber deviation evident from the sloping fracture plane

7. TEST RESULTS

7.1 General

A very good correlation between the MOE's determined by ultra-sound wave velocity resp. from elongation in tension testing was obtained; these results will be discussed separately. In the following, for all strength vs. MOE correlations the directly measured tension MOE, $E_{t,0}$, of the less stiff of both jointed laminations is used.

The failure of the joints was in all cases very brittle. In the strength tests the load displacement curves were completely linear up to about 70 % of the ultimate load. Figures 4a, b show views of typical failure appearances obtained in the tension tests.

The measured fiber deviations were in the range of 0 to 6 degrees except for batches A and E where fiber deviations were in the range of 6 to 10 degrees.

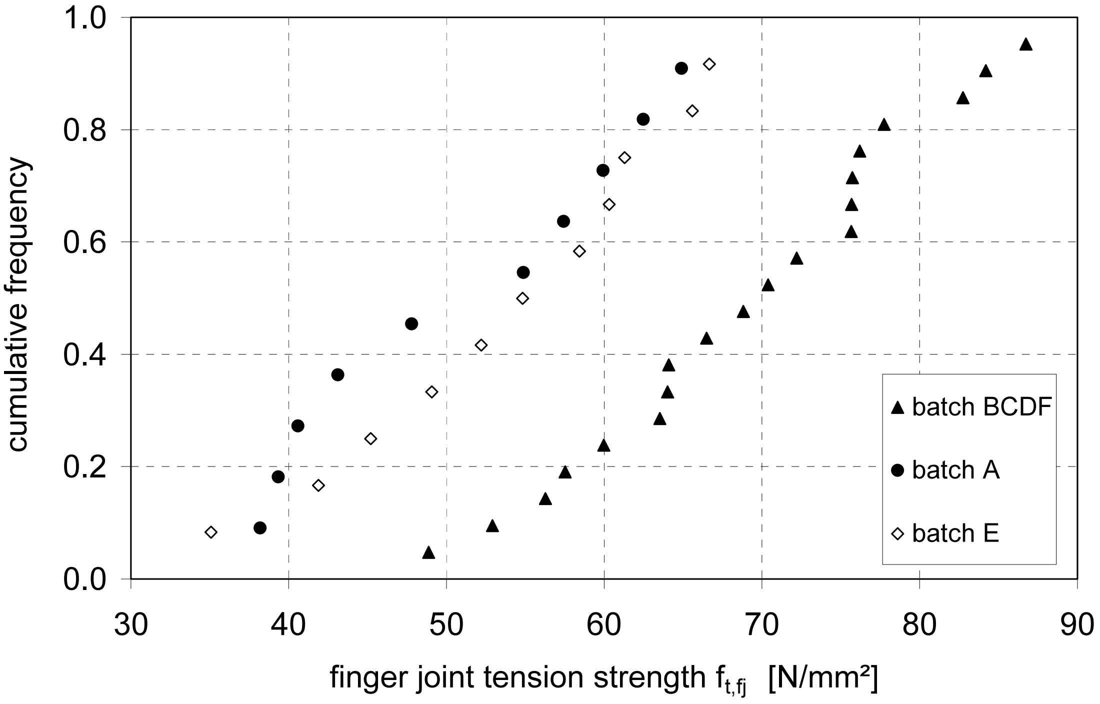
Table 3: Compilation of finger joint tension strengths of different lamination batches and percentages of "pure" finger joint failures

batch	density range ρ_{12}	No. of joints	"pure" finger joint failures	finger joint tension strength				
				mean	std.	C.O.V.	min	max
-	kg/m^3	-	%	N/mm^2	N/mm^2	%	N/mm^2	N/mm^2
BCDF	640 - 680	8	100	64,4	12,7	19,7	48,9	84,2
BCDF	680 - 720	13	85	72,0	8,1	11,3	60,0	86,7
BCDF	all specimens	21	90	69,0	10,6	15,4	48,9	86,7
A	670 -700	10	20	50,9	10,2	20,0	38,2	64,9
E	670 –720	4	25	49,6	13,2	26,6	35,1	61,3
E	720 - 770	7	17	56,0	8,1	14,4	45,2	66,7
E	all specimens	11	18	53,7	10,1	18,8	35,1	66,7

Table 3 contains a compilation of finger joint tension strength of the individual finger joint batches. Given are means, C.O.V.'s and extreme values. Additionally the percentages of "pure" finger joint failures are given. A "pure" finger joint failure is characterized by a failure in the joint line, either along the finger slopes (Fig. 4a) or in the net cross-section or mixed. Failure appearances acc. to Fig. 4b where the failure line deviates partly considerably or completely from the joint line are termed “not pure” finger joint failures. These failures were throughout associated which an expressed fiber deviation coinciding with the sloping fracture plane.

Figure 5a depicts the empiric cumulative frequency of finger joint tension strengths of batch BCDF; further the cumulative frequencies for strengths of batch A and batch E are given. The graph shows “two” distinctly separate distributions, ***one*** being the cumulative frequency of batch BCDF and the ”***other”*** the closely similar distributions of finger joint batches A and E.

Additionally to the cumulative strength frequencies given for different stem batches (Fig 5a), Fig. 5b shows the cumulative strength frequencies for different classes of modulus of elasticity $E = E_{t,0}$. The joints are classified into a specific class according to the MOE of the less stiff of both jointed laminations. The respective MOE class ranges (in N/mm^2) are $E < 11000$, $11000 < E < 13000$ and $E > 13000$. The lowest MOE class consists exclusively of joints of batch A and the second lowest MOE class consists to a high percentage (70%) of the joints of batch E (see also Fig. 7b). The highest MOE class consists almost entirely of joints from batch BCDF.



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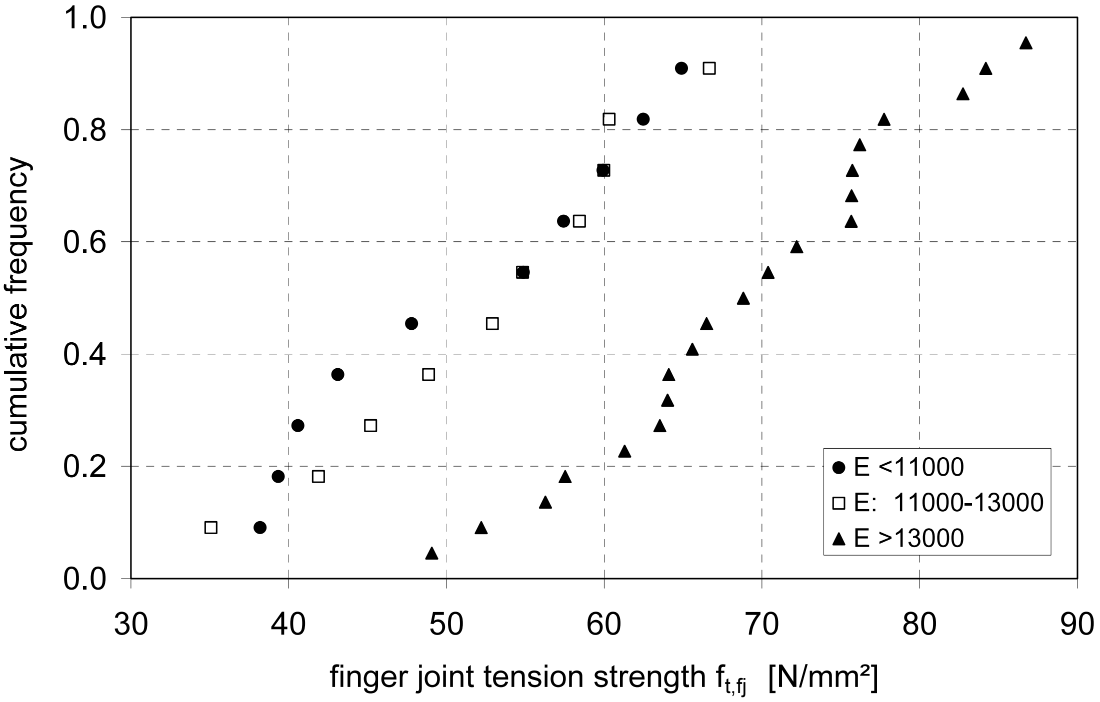


b)

Fig. 5a, b: Cumulative frequency of finger joint strength
a) for different lamination batches
b) for different classes of modulus of elasticity $E = E_{t,0}$

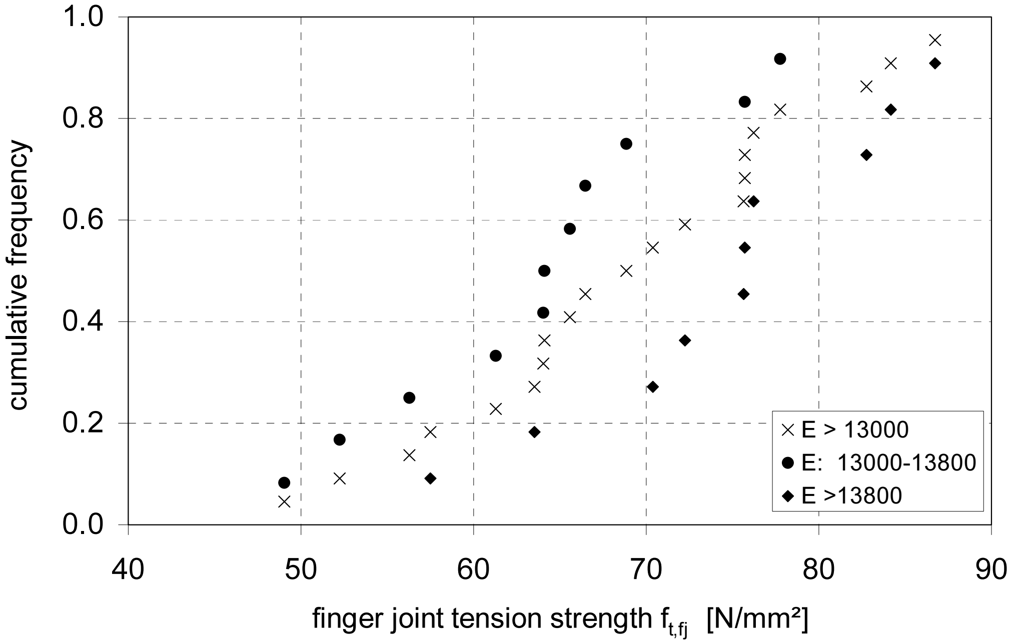


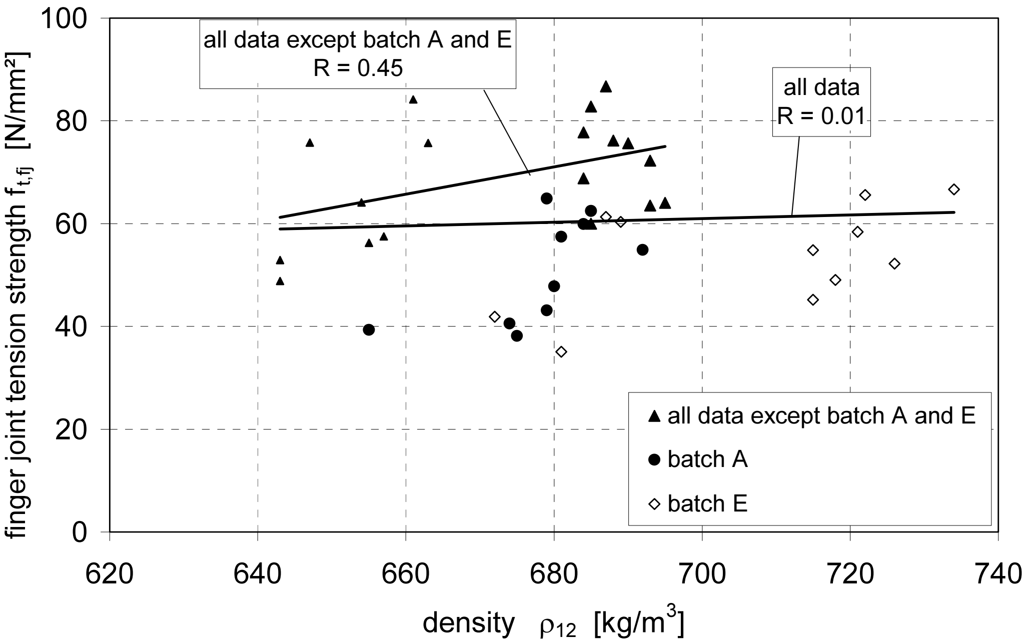
Fig. 6: Cumulative frequency of finger joint strength of the MOE class > 13000 split up in two MOE sub-batches with almost equal specimen numbers

The reason that the cumulative frequencies of batches A and E differ only very little, although differentiated significantly by MOE, is strongly related to the failure mode obtained for batches A and E. In both batches predominantly "not pure" finger joint failures, bound to high fiber deviation, were obtained (compare Tab. 2).

In order to illustrate the influence of MOE on strength, excluding the effect of fiber deviation, Fig. 6 shows the cumulative frequency of MOE class $E > 13000$ N/mm^2 split up in two MOE sub-batches with almost equal specimen numbers. One batch comprises the MOE range $13000 < E$ [N/mm^2] < 13800 and the other consists of specimens with $E > 13800$ N/mm^2. A clear separation of both sub-batches throughout the whole cumulative frequency range is obvious.

7.2 Strength vs. MOE /density correlations

Figure 7a shows the relationships between the finger joint tension strength $f_{t,fj}$ and density ρ_{12}. Also given are the linear regression lines and coefficients of variations for different batches. In case that all data are regarded, no correlation at all exists between $f_{t,fj}$ and ρ_{12}. However, when batches A and E are excluded, a slight $f_{t,fj}$ vs. ρ_{12} correlation evolves as the joints with high fiber deviation are excluded.



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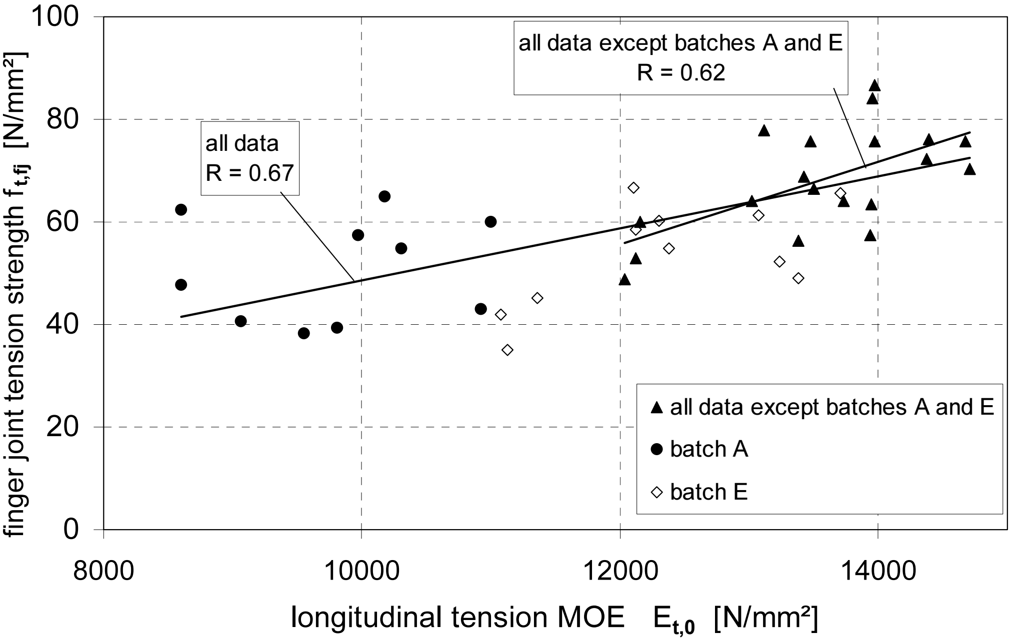

b)

Fig. 7a, b: Correlation between finger joint tension strength and
a) density ρ_{12}
b) longitudinal tension modulus of elasticity $E_{t,0}$

Figure 7b depicts the relationship between finger joint tension strength $f_{t,fj}$ and tension MOE $E_{t,0}$. The coefficient of correlation of the linear regression for all data is 0,67 and in case of exclusion of batch A and E the correlation coefficient R = 0,62 is obtained.

8. CONCLUSIONS

The performed study allows the following conclusions:

- Finger jointing of beech wood laminations is principally well feasible in industrial conditions when jointing pressure is adequately adjusted as compared to softwood jointing.
- Excluding two stems with high fiber deviations, a mean finger joint tension strength of about 70 ± 11 N/mm^2 was obtained.
- Fiber deviation is a far more critical issue compared to finger jointed softwood laminations, as it is very hard to detect.
- Density of the laminations is a poor indicator for finger joint strength as it does not reflect the influence of fiber deviation.
- Tension MOE of the laminations shows a decent correlation with finger joint strength.
- A good correlation was obtained between MOE's determined by ultrasound wave velocity and direct elongation measurements.
- The finger joint tension strength range of 80 – 100 N/mm^2 indicated in literature was not confirmed in this study.
- Solving the issue of fiber deviation, finger jointed beech laminations will foreseeable lead to high strength glued timber beams.

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