

MECHANICAL PROPERTIES OF A NEW STRUCTURAL COMPOSITE LUMBER PRODUCT "CROSS-BEAM" WITH EMPHASIS ON SHEAR CAPACITY

MECHANISCHE EIGENSCHAFTEN EINES NEUEN TRAGENDEN BALKENARTIGEN HOLZ-COMPOSITS „KREUZBALKEN“ UNTER BESONDERER BERÜCKSICHTIGUNG DER SCHUBTRAGFÄHIGKEIT

CARACTERISTIQUES MECANIQUES D'UNE NOUVELLE POUTRE STRUCTURALE EN BOIS COMPOSITE "POUTRE-CROISÉE" AVEC INSISTANCE SUR LE COMPORTEMENT AU CISAILLEMENT

Simon Aicher

SUMMARY

It is reported on some aspects regarding built-up and material properties of a new reconstituted structural wooden beam product, called Cross-Beam. Emphasis is laid on shear capacity. Cross-Beam is built-up from four segments with pentagonal cross-sections. Each of the segments resembles coarsely one quarter of a stem sawn cross-wise, with the peripheries of the quarter circles processed to three edges. The segments are glued together such that the pith corners of the segments then form the four corners of the rectangular cross-section of the beam. Hence, this results in an interior rhombic hole in the center of the cross-section. The hole is subject to specified relative maximum sizes.

The mechanical behaviour of the described innovative product has been investigated intensively at the timber department of FMPA – Otto-Graf-Institute – for the purpose of a general German building approval. The specific built-up obviously affects the apparent stiffness and strength properties differently in specific types of loading. It is shown in detail that shear capacity resp.

strength of the structure are significantly higher than expected from elementary beam analysis and quasi isotropic material behaviour within the cross-section.

ZUSAMMENFASSUNG

Es wird über einige Aspekte betreffend Aufbau und Materialeigenschaften eines neuen tragenden, durch Verklebung hergestellten Holzbalkens mit der Produktbezeichnung „Kreuzbalken“ berichtet. Vertiefend wird die Schubtragfähigkeit behandelt. Der Kreuzbalken ist aus vier Segmenten mit jeweils fünfeckigem Querschnitt aufgebaut. Jedes der Segmente ähnelt grob einem Viertelholz eines kreuzweise aufgetrennten Stammes, wobei die Viertelkreisberandungen der Segmente dreikantig bearbeitet sind. Die Segmente werden derart miteinander verklebt, daß die marknah gelegenen Ecken der Segmente sodann die vier Ecken des rechteckigen Balkenquerschnitts bilden, wodurch sich eine in der Querschnittsmitte befindliche, rhombusähnliche Aussparung ergibt. Die Lochgröße muß festgelegten relativen Höchstmaßen genügen.

Das mechanische Verhalten des beschriebenen innovativen Produkts wurde in der Holzabteilung des Otto-Graf-Instituts (FMIPA) eingehenden Untersuchungen zum Erhalt einer allgemeinen bauaufsichtlichen Zulassung unterworfen. Der spezifische Aufbau beeinflusst naheliegend die scheinbaren Steifigkeits- und Festigkeitseigenschaften bei verschiedenen Beanspruchungsarten unterschiedlich. In detaillierterer Weise wird aufgezeigt, daß die Schubtragfähigkeit bzw. -festigkeit des Bauteils deutlich höher ist als zufolge gewöhnlicher Balkentheorie in Verbindung mit quasi isotropem Verhalten innerhalb des Querschnitts zunächst anzunehmen ist.

RESUME

Un rapport est donné sur quelques aspects concernant la structure et les caractéristiques de matériau d'une nouvelle poutre en bois composite, appelée Poutre-Croisée. La portance au cisaillement est analysée. La poutre est composé de quatre segments avec une section pentagonale. Chaque segment ressemble à un quart de tronc scié en croix, avec les périphéries des quarts de cercle travaillés de façon à obtenir surfaces planes. Les segments sont collés l'un à l'autre de manière que les angles provenant du centre du tronc forment les quatre angles de la section rectangulaire de la Poutre-Croisée, d'où résulte un trou rhombiforme au milieu de la section. Les dimensions du trou sont limitées par des valeurs maximales fixées

Le comportement mécanique du produit innovateur décrit a été analysé en détail dans le département du bois de la FMPA – Institut-Otto-Graf – pour obtenir une homologation allemande. La structure spécifique influence les propriétés de rigidité et de résistance différemment sous des efforts spécifiques. Il est montré en détail que la portance, respectivement la résistance au cisaillement sont nettement plus élevées que prévisibles selon avec la théorie des poutres combinée avec un comportement quasi-isotrope dans la section.

Key-words: Cross-Beam, reconstituted wood, structural composite lumber, shear capacity, characteristic material properties

1 INTRODUCTION

Reconstituted wood products are built up from adhesive joined smaller wooden particles or components. They show increased and more reliable mechanical performances in the specific field of application, compared to the unprocessed raw material wood, which incorporates a number of growth bound defects resp. geometric restrictions. Increasingly, the best possible fiber utilization has to be pursued, due to economical as well as ecological demands.

In recent years, a variety of new reconstituted wood products such as LVL, PSL, LSL – with distinct differences compared to products established earlier, such as plywood, particle or fiber board and OSB – have been developed for structural use in the building market. Laminated Veneer Lumber (LVL), the first development in this field, has evolved to a highly differentiated product since its first conception in the early seventies. Product sophistication relates to veneer joints, NDT based grading and quality control of veneers and specific cross-sectional built-ups. Brand names approved for the German market are KERTO LVL (N.N. 1996a) and MICROLAM LVL (N.N. 1993). Parallel Strand Lumber (PSL), known by the brand name PARALLAM PSL (N.N. 1994), serving as a reconstituted beam product, is built up from very long (400–2000 mm) and slender parallel oriented strands. Its extremely advanced production technology incorporates high frequency curing.

The latest North American product Laminated Strand Lumber (LSL) combines production and behaviour features of OSB, made from spacious flakes, and PSL.

All aforementioned engineered wood products, frequently termed engineered wood or structural composite lumber (SLC) products, are built up from thin and, apart from LVL, small constituents with a rather high degree of processing compared to the input material " log ". Apart thereof, a second category of engineered wood products built up from larger board or lumber like constituents emerged. Promising products in this field seem to be HQL-lumber (N.N. 1995), a board-like product, and Cross-Beam (N.N. 1996b), a beam product. Some aspects of this latter innovative product are discussed following with special consideration to shear capacity.

It should be mentioned that all cited brands of reconstituted wood products have been resp. are investigated for German general building approval by the Timber Department of the FMPA – Otto-Graf-Institute.

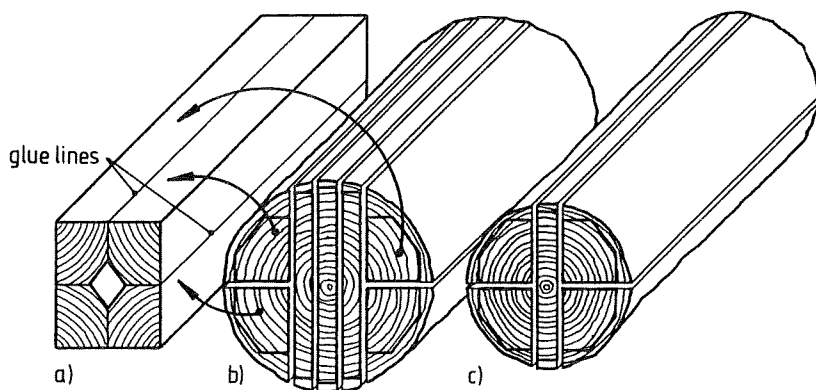
2 PRODUCT AND PRODUCTION FEATURES

2.1 General remarks

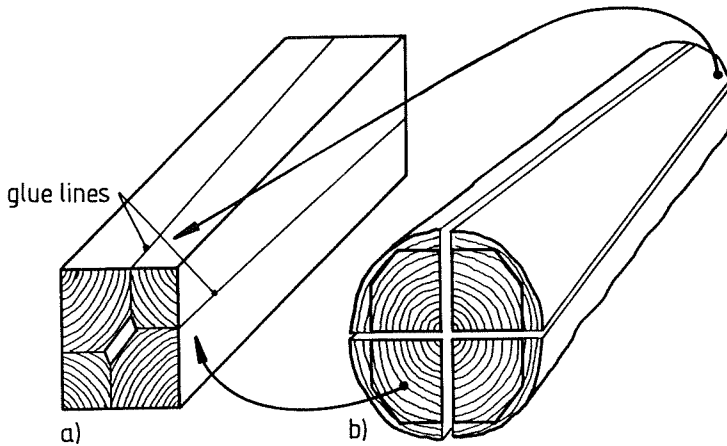
The product Cross-Beam with the complementary descriptive attribute "built up from parallel constituents" is a wooden beam with rectangular outer cross-section and a centric rhombus shaped hole inside(Fig. 1a). The specific shape results from the cross-wise gluing of four segments as indicated schematically in Figs. 1b, c, whereby the corners of the segments coming from the pith then define the corners of the gross cross-section. By approval specification (N.N. 1996b), the segments are to be sawn exclusively from softwoods, must not include pith and can be sawn deliberately either from side ware boards (Fig. 1b) or, especially in case of smaller cross-sectional dimensions, from quarter-sawn stems (Fig. 1c).

The complementary descriptive attribute "built up from parallel constituents" refers to the fact that the segments are to be sawn parallel to the axis of the stem, as usual in today's sawmilling technique, which results in a significant loss of raw material due to growth dependent conical shape of a stem. The latter deficiency is overcome with an advanced Cross-Beam product built up from conical segments, then sawn parallel to fiber direction. Hereby the generally no longer symmetric cross-section (Fig. 2a) is constituted in such a way, that the tapers of both pairs of diagonally opposite segments are inverted (Fig. 2b). An economic production of the so-called conical Cross-Beam is bound to new sawing and chipping equipment which is intensively developed at the moment; some beam prototype testing has already been performed at the FMFA. However, further time will be necessary to establish a reliable production.

The following discussion is restricted to some aspects of the approval of the Cross-Beam made from parallel sawn constituents.



Figs. 1a-c: Built-up and production alternatives of Cross-Beam made from "parallel constituents"



Figs. 2a, b: Built-up and production of Cross-Beam made from „conical constituents“

2.2 Built-up specifications

According to general German building approval specifications, the cross-sectional dimensions are at the time restricted to the size range ($B \times H$) from 8×10 to 20×26 cm, with an admissible edge length ratio of $H/B \leq 2$, where $H \geq B$. Total length and free span must not exceed 12 resp. 6 m¹. The total glue line lengths B_n , H_n along cross-sectional width resp. depth (Fig. 3) are bound to minimum requirements, as specified in eqs. 1a-c:

¹ The quoted dimensional restrictions shall hold until enough satisfactory production and field experience has been gathered; this is in line with comparable procedure in glulam production certification in Germany.

$$B_n = 2 b_n \geq 0,6 B ,$$

$$H_n = 2 h_n \geq 0,55 H \quad \text{and} \quad H_n \geq 0,6 B . \quad (1a-c)$$

Subsequently throughout the allowable minimum values of B_n and H_n are assumed.

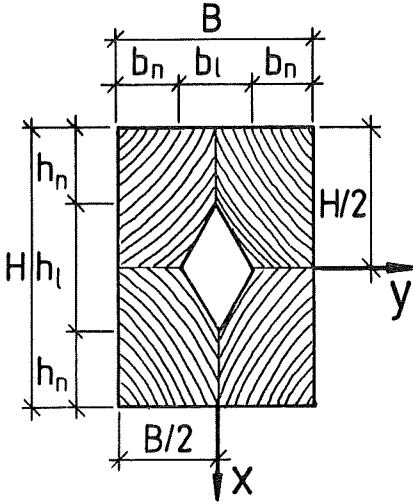


Fig. 3: Cross-section of a Cross-Beam with edge notations

Cross-Beams can be produced in two grades termed S10 and S13, defined e.g. by characteristic bending strength values of 24 resp. 28 N/mm². The visual grading of both strength classes is primarily based on solid lumber grading rules acc. to German grading standard DIN 4074, part 2, but also incorporates extra grading specifications taking into consideration the specific cross-sectional built-up.

Cross-Beams may incorporate finger joint connections over the entire cross-section (large finger joints), but no finger joints in the segments. At least

for the superior grade S13, the finger joints are indispensable with respect to manufacture of longer beams, as it becomes increasingly hard to meet the prescribed grading requirements for knots without use of finger joints. The minimum distance of two adjacent finger joints is prescribed as ≥ 2 m.

Several further product and production specifications, related e.g. to size tolerances and adhesives are left aside in this context.

3 APPROVAL CONCEPT PURSUED

The approval concept is based on the best possible design of the product with regard to geometry of the full gross cross-section. This means that eventual reductions of strength resulting from the net cross-sectional built-up have to be reflected by the assigned apparent strength values (Table 1). Such an approach is rather trivial when performing the task conservatively by sole consideration of beam theory and net cross-section. Then however, a profound underestimation of the true load capacity may be obtained, for instance in the case of shear, as shown subsequently.

In the case of bending, it is obvious from the equations for the effective moment of inertia resp. section moment (given here for y-y gravity axis)

$$I_{y, eff} = \frac{BH^3}{12} - \frac{b_l w_l^3}{48} = \frac{BH^3}{12,0773}, \quad W_{y, eff} = \frac{BH^2}{6,0387} \quad (2a, b)$$

that bending strength will not be affected unfavourably by the hole. The quantities I_{eff} , W_{eff} are reduced by less or maximally 1 %, compared to the full gross cross-section. On the contrary, the minor reduction in section moment should be well compensated by the specific built-up with two load sharing segments across width, providing a more redundant behaviour. The latter was proven in extensive bending tests, not considered in this paper.

Table 1: Characteristic strength and stiffness properties in N/mm² (and densities in kg/m³) for Cross-Beams acc. to building approval Z-9.1-314 (N.N. 1996b); for comparison, properties for glulam with homogeneous built-up, specified for strength classes GL 24 and GL 28 in prEN 1194: 1995 are given, too

Cross-Beam resp. glulam grade resp. strength class		Cross-Beam		glulam	
		S10	S13	GL 24 h	GL 28 h
Bending strength	$f_{m, k}$	24	28	24	28
Tension strength					
parallel to grain	$f_{t, 0, k}$	14,8	17,8	17	19,5
perp. to grain	$f_{t, 90, k}$	0,27	0,27	0.35	0,45
Compression strength					
parallel to grain	$f_{c, 0, k}$	21,0	23,0	26	28
perp. to grain	$f_{c, 90, k}$	4,5	4,5	5,1	5,6
Shear strength	$f_{v, k}$	2,7	2,7	2,1	2,5
Modulus of elasticity					
parallel to grain	$E_{0, mean}$	10500	12000	10800	12500
	$E_{0, 05}$	8500	9500	8600	10000
perp. to grain	$E_{90, mean}$	370	400	360	410
	$E_{90, 05}$	250	270	–	–
Shear modulus					
	G_{mean}	690	750	670	780
	G_{05}	460	500	–	–
Density	ρ_k	380 ¹⁾	380 ¹⁾	360	400

- 1) Not explicitly stated: in context with here not discussed specifications for mechanical fasteners, given values apply conservatively.

Tension and compression bearing capacities parallel to beam axis should be reduced by roughly 10 % compared to the full cross-section, due to a maximum ratio of net to gross area ratio of

$$A_{eff} / (BH) = 0,89; \quad (3)$$

the actually assigned tension and compression strength values, validated by test results, incorporate this assumption and further considerations on finger joints, too.

In tension perpendicular to grain, an admittedly rather unimportant loading for straight beams, a strength reduction acc. to the ratio of minimum net to gross width $B_n / B = 0,6$ seemed appropriate and was assigned. The latter reduction should also hold true for shear strength at first view.

Assuming homogeneous, quasi isotropic material behaviour within the cross-section, and denoting f_v as shear strength of the segments, i. e. of not discontinuous wood, the shear force capacity in bending due to elementary beam analysis should be ($S_{y, eff} = BH^2/8,1744$)

$$V_f = f_v \frac{I_{y, eff}}{S_{y, eff}} B_n = \frac{2}{3} f_{v, app} BH \quad (4a, b)$$

where $f_{v, app} = 0,61 f_v \approx f_v B_n / B$.

The quantity $f_{v, app}$ is the apparent shear strength related to the gross cross-section. Obviously, a derived 40 % strength reduction of shear capacity could in many cases prevent full utilization of the high bending strength properties. However, wood, and of course reconstituted wood products are specific materials in many respects. Based primarily on former experience from approval testing of vertical glulam (Aicher, 1990), it could be presumed that the apparent shear strength would probably be higher than predicted by eq. (4b).

This assumption is bound to the specific annual ring pattern especially in the neutral fiber area.

In order to provide an empirical basis for realistic shear design, comprehensive tests were performed.

4 SHEAR TESTS

4.1 Material

The tests were performed with cross-sectional dimensions of (B x H) 8 x 10, 10 x 20, 14 x 14, 16 x 23 and 20 x 20 cm, covering well the approval size range. The hole geometries conformed in general to those prescribed by eqs. (1); the average dimensional ratio $B_h/B = 0,63$ was slightly higher compared to the specified requirement. The densities of the specimens, determined from cross-sectional slabs of 50 mm width taken from the areas of shear failure, varied in a rather narrow range. The mean density, standard deviation and C.O.V. = V of all specimens at nominally 12 % moisture content (MC) were

$$\rho = 429 \pm 26 \text{ kg/m}^3, \quad V = 6,1 \% .$$

Disregarding the fact that densities were not well normal distributed but positive skew, the characteristic density quite similarly for normal, lognormal and Weibull distribution was $\rho_k = 393 \text{ kg/m}^3$. The beam specimens (see below) were cut from longer unjointed beams used for shear and bending tests.

4.2 Test set-up and procedure

At the present time, no national resp. international standard exists specifying the determination of shear capacity resp. strength of structural size

timber beams. Here shear strength tests were carried out as four point bending tests; Fig. 4 shows the scheme of the test set-up. Due to the specific ratios of strengths of wood in bending, shear and compression perpendicular to the grain, determination of shear strength in a bending test is a problematic issue.

In order to exclude potential bending failures resp. crushing in the load application areas, Korin (1988) proposed bending tests with an artificial reduction of the rectangular cross-section through both-sided horizontal notches at mid-depth along the full length of the beam. In case of the investigated glued cross-sectional built-up, showing already a major reduction of the shear area, this idea was not further pursued.

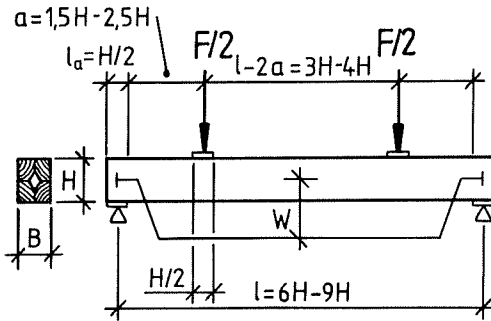


Fig. 4: Scheme of test set-up

The probability of shear failure is bound to sufficient small ratios of bending moment vs. shear force. Elementary statics delivers as minimum condition for dimensional ratio a/H in the case of four point bending ($M_f = V_f a$)

$$a/H \leq 0,25 (f_m / f_v) (B/B_n) . \quad (5a)$$

Alike, avoidance of crushing failures through sufficient load bearing length l_a requires a ratio of

$$l_a / H > 0,67 (f_v / f_c, 90) (B/B_n) \quad (5b)$$

In a very rough approximation, the ratio of bending to shear strength for softwoods (solid and glulam) in structural dimensions can be assumed in the range of $f_m / f_v \approx 10 \dots 12$. The ratio of compression perp. to shear strength obviously largely depends on the definition of compression strength; in a rough estimation, this ratio may be assumed as 1,3–2. Based on given strength ratios, eqs. (5a, b) deliver in case of a full cross-section ($B_n = B$) maximum resp. minimum ratios of $a/H \leq 2,5$ and $l_a/H \geq 0,5$ to obtain shear failure probability. Remember that the derived dimensional ratios for a/H , l_a/H are based on crude elementary beam analysis and shall solely enable an estimation of the test set-up. More profound, nonlinear continuum analysis should be applied.

The actually employed ratios a/H , a/l and l/H varied, depending on cross-sectional sizes, from $1,5 \leq a/H \leq 2,5$, $0,21 \leq a/l \leq 0,28$ resp. $6 \leq l/H \leq 9$. In detail, cross-sections 8 x 10 and 14 x 14 cm were tested with $a/H = 2,5$, $a/l = 0,21$ and $l/H = 9$. Due to an increasing rate of bending failures with cross-sectional dimensions of 10 x 20 cm, the ratio a/H was reduced to 1,5 for the majority of the 10 x 20 cm specimens ($l/H = 7$, $a/l = 0,21$) as well as for sizes 16 x 23 cm ($l/H = 7$, $a/l = 0,21$) and for 20 x 20 cm ($l/H = 6$, $a/l = 0,25$). The reduced ratio $l/H = 6$ in case of 20 x 20 cm cross-sections resulted from limited total beam length, cut to bending and shear test specimens. For all specimens bearing length ratio l_a/H was 0,5.

Mid-span deflection was measured with two opposite LVDT's, recorded altogether with the load signal by PC controlled data acquisition equipment. The tests were performed in quasi load control, with times to failure in the range of 300 ± 120 sec as specified in DIN EN 902 for bending tests. After failure, densities and moisture contents were determined within the fracture areas.

4.3 Results

The load vs. mid-span deflection curves of all 41 specimens were almost linear up to about 2/3 of the ultimate load. In the last third of the loading range, throughout a slight nonlinearity was encountered and some specimens showed pre-peak load drops and subsequent load recovery.

As failure modes, brittle shear failures in one of both support areas were obtained with 28 specimens (= 68 % of the test scope); slightly less than 1/3 of the specimens failed in bending. The bending failure frequency was not significantly higher for any specific cross-sectional dimension. The best fits to the empirical apparent shear strength data of specimens failed in shear were obtained quite similarly for Gaussian and 3parameter Weibull distributions (Fig. 5). The mean (\pm standard deviation, C.O.V. = V) and characteristic value (lower 5 % fractile) acc. to normal distribution were

$$f_{v, app, mean} = 4,70 \pm 0,65 \text{ N/mm}^2, \quad V = 13,8 \%, \quad f_{v, app, k} = 3,65 \text{ N/mm}^2.$$

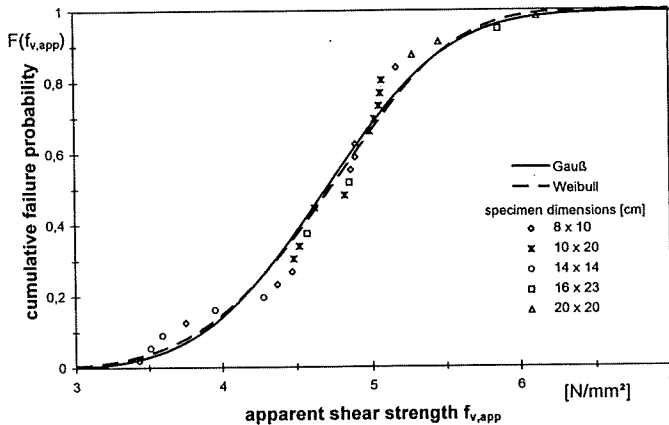
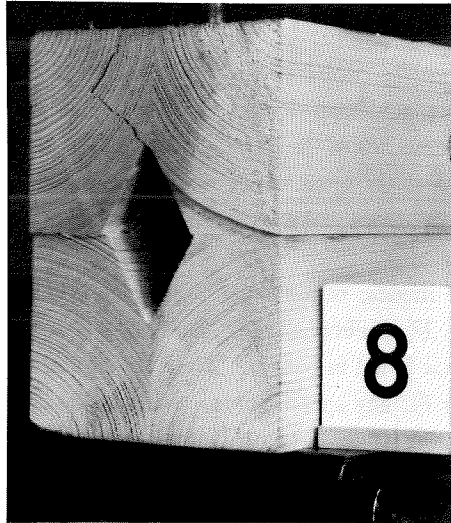


Fig. 5: Cumulative distribution of experimental shear strength results and fitted statistical distribution

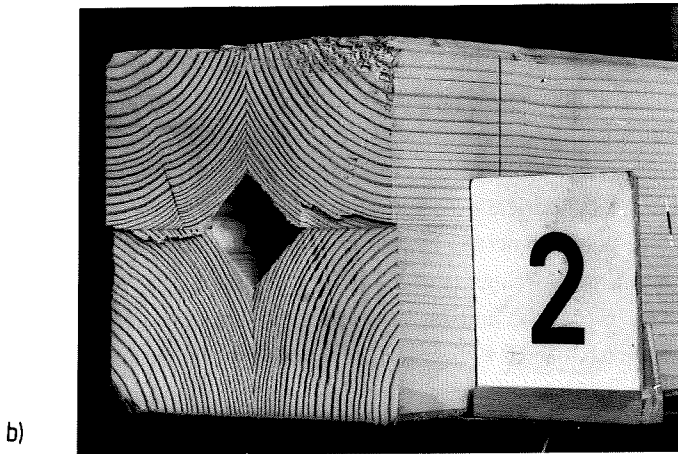
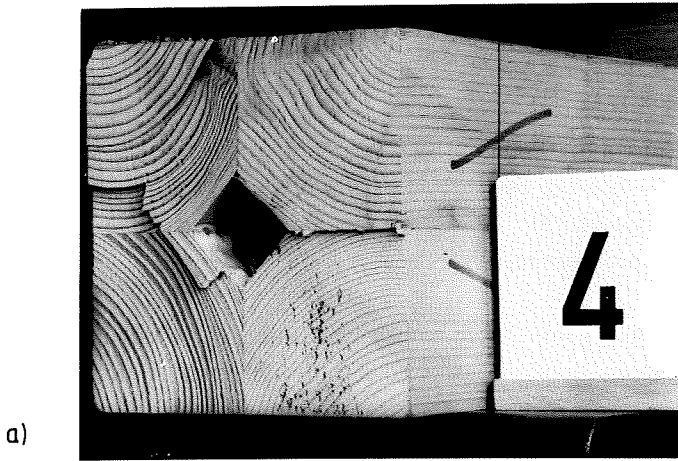


a)



b)

Figs. 6a, b: Typical shear fracture appearance of Cross-Beam viewed at end cross-section



Figs. 7a, b: Typical shear fracture appearance of Cross-Beam viewed at end cross-section

The characteristic value acc. to Weibull distribution

$$F(f_{v,app}) = 1 - \exp \left[- \left(\frac{f_{v,app} - 2,22}{2,72} \right)^{4,3} \right]$$

amounts to 3,58 N/mm². The test results yielded no statistical correlation ($r = 0,14$) between apparent density and shear strength in the investigated density range of 390 – 490 kg/m³. The regression analysis even shows a slight negative trend of strength vs. density.

The obtained mean and characteristic shear strength values are rather high compared to those usually obtained for full cross-sections of lumber resp. glulam (see Table 1). The reason for the high shear strength values, obviously not reflecting the strong effective width reduction $B_n/B = 0,6$ in the neutral fiber plane, can be explained by the fracture surfaces.

Figs. 6a, b and 7a, b show typical failure appearances within the end cross-sections, revealing that the fracture planes coincide only partially with the neutral fiber plane. For all specimens, the fracture plane deviated at least in one half of the cross-section from the neutral axis, following differently accentuated the cylindrical resp. conical annual ring structure. In several cases the fracture plane coincided completely with the early-late wood boundary of two adjacent annual rings (Fig. 6a). The prevailing failure appearances were those given in Figs. 6b and 7a, b; the failure planes are not steadily cylindrical but deviate stepwise in radial direction, followed by further tangential propagation. The fracture surfaces, altogether with the high shear strength values highlight the specific product behaviour in shear transfer. The specific annual ring pattern in the glued interface with obviously high shear resistance causes pronounced deviations of the failure planes from the neutral axis, following the cylindrical material anisotropy in stiffness and strength. This results in a significantly increased shear transfer area compared to elementary isotropic assumptions.

The experimental investigations allowed to omit the severe reduction of factor $B_n/B = 0,6$ in eq. (4b) for the determination of apparent shear strength. The actually assigned characteristic strength values $f_{v, app, k} = 2,7 \text{ N/mm}^2$ thus could be chosen equal to those specified for German glulam grades BS 11, BS 14, which in general conform to European glulam grades GL 24, GL 28.

5 REFERENCES

Aicher, S. (1990): Investigations on the torsion properties of vertical glulam including „warping torsion“ of orthotropic materials. Otto-Graf-Journal, Vol. 1, pp. 9–35

Korin, U. (1988): Shear strength in bending of timber. Proceedings CIB W18A meeting 21, paper 21-6-3, Parksville

N. N. (1993): General German building approval Z-9.1-245 issued by DIBT. Product: Furnierschichtholz „Micro = LAM LVL 2.0E“; applicant: Trus Joist McMillan; 1st approval date: February 1993

N. N. (1994): General German building approval Z-9.1-241 issued by DIBT. Product: Furnierschichtholz „Parallam PSL“; applicant: Trus Joist McMillan; 1st approval date: February 1993

N. N. (1995): General German building approval Z-9.1-287 issued by DIBT. Product: „HQL-Holz“; applicant: Palsgard Trae; 1st approval date: August 1995

N. N. (1996a): General German building approval Z-9.1-100 issued by DIBT. Product: „KERTO“ – Furnierschichtholz; applicant: Finnforest Oy; 1st approval date: March 1981

N. N. (1996b): General German building approval Z-9.1-314 issued by DIBT.
Product: „Kreuzbalken aus parallelen Vormaterialien“; applicant:
Konstruktion-Holz-Werk (KHW) Seubert; 1st approval date: July
1996