Laminated veneer lumber hollow cross-sections for temporary soil nailing

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Abstract

An innovative approach using laminated veneer lumber (LVL) hollow sections for temporary geotechnical slope stabilisation is being presented within this article. The use of circular laminated veneer lumber hollow sections as reinforcement elements in soil nailing walls demands load bearing elements, primarily loaded in tension, with a length up to 10 m. Thus finger-jointing was found to be an efficient method of a longitudinal load-carrying connection in combination with a minimized cross section reduction at the joint. This paper discusses the applicabiltiy of finger jointing on beech wood laminated veneer lumber hollow sections and presents the results of large scaled tensile under variaton of the joint arrangement.

1. Introduction

Currently, soil nailing is a common way of slope stabilization in foundation engineering. Therefore, steel anchors are drilled into the soil and a reinforced shotcrete layer protects the slope surface. The gap around the steel rod is filled with cement grout. The hardened cement body ensures the necessary connection (force closure) between soil and anchor. For the stabilization of construction pit slopes, usually temporary soil nailing systems are used. In case of temporary soil nailing systems, the construction has a reduced service life of maximum two years. Thereafter, the anchors have no structural utility, but usually remain in the soil, because generally it is not possible to remove them due to their limited accessibility after their installation. The objective in this research topic is to replace the temporary steel nails by curved laminated hollow sections CLHS manufactured from European beech *(Fagus sylvatica L.)* in reinforced cut slopes.

Figure 1: Beech curved laminated hollow sections CLHS prototypes (left) and related cross section with 100 mm outer diameter and 18 mm wall thickness

The motivation is to develop a sustainable soil nailing system for temporary purposes in combination with a new way of using beech wood by combining both positive and negative beech material properties (high strength and low durability). The wooden soil reinforcement elements decompose in the soil after fullfilling their expected service life. Figure 2a shows a typical slope excavation supported by a shotcrete layer and steel nails, and Figure 2b illustrates the method using wood-based reinforcement elements.

a) Standard soil nailing system (b) Slope stabilisation using wooden hollow cross-sections

Figure 2: Current soil nailing system (a) and investigated temporary method (b)

Since the construction of the first reinforced soil walls (RSW), the first approaches of design methods were developed based on the results of large-scale field tests (Gäßler und Gudehus 1981; Gäßler 1987; Project National Clouterre 1991). Generally, the reinforced soil in combination with the soil facing is assumed to form a composite body, resisting externally-acting lateral and vertical forces. To ensure the internal bearing capacitiy of the reinforced soil body (internal stability), besides numerical methods, various other design concepts were developed based on mechanical limit equilibrium considerations of rigid body motions. Existing slope stability analysis methods, where external forces act on the rigid body, are compared to mobilised resistances in the soil and extended by reinforcement elements. Tensile elements were added to the equilibrium consideration, which increase the resistance to the external driving forces. However, these extended conventional slope analysis procedures based on LE considerations only assign axial forces to the nails to fulfill the equillibrium. The design concept following Gäßler 1987, considering two translation bodies and polygonal slip lines, is the theoretical concept of the internal stability design given in Design guide line RVS 09.01.41 for instance. Thus, based on current state of the art design methods, only tensile forces are considered as acting forces in the reinforcement elements.

Bar-shaped elements for load-bearing timber structures are usually made of solid wood or wooden engineered products like glue laminated timber (GLT), cross laminated timber (CLT) or LVL. With regard to production cutting losses, processing issues and the structural design of constructions and connections, rectangular cross-section geometries are usually preferred for load-bearing timber elements. However, cement grouted soil nails act as a composite element similar to reinforcement bars in concrete structures due to the force transformation from the soil into the bar. Therefore, the nail´s tensile capacity and the bonding behaviour between the nail and the surrounding cement is essential and depends significantly from the available contact surface between the bar and the cement grout. Inspired by blades of grass, circular ring-shaped cross-sections offer a high stability performance due to the optimised proportion between moment of inertia $I_{Y,Z}$ and cross-section area A_t. Additionally, a circular cross-section of reinforcement members offers an improved proportion between outer periphery U_{out} and A_t compared to rectangular geometries (Figure 3) and is therefore preferably used for reinforcement elements primarily loaded in tension. Because of practical concerns, CLHS for soil nailing have to be installed by caused drillings. An installation similar to a self-drilling anchor is not possible from technical reasons at the moment. The outer diameter d_t of the LVL-nail is limited to about 100 mm due to a common bore hole diameter of about 140 mm and a minimum thickness of the surrounding cement body of 20 mm. The wall thickness t of the poles is given by the tensile force in the nail as well as the minimum possible curvature of the veneers in the inner diameter d_i without destruction of the veneer perpendicular to the fiber direction. A wall thickness of approximately 18 mm (6 layers of 3 mm thick veneers respectively) and an inner diameter d_i of 64 mm was found to be suitable for the manufacturing process without crushing the innermost veneers and had been adopted for all investigations. The fiber direction of all veneer layers corresponds with the pole axis.

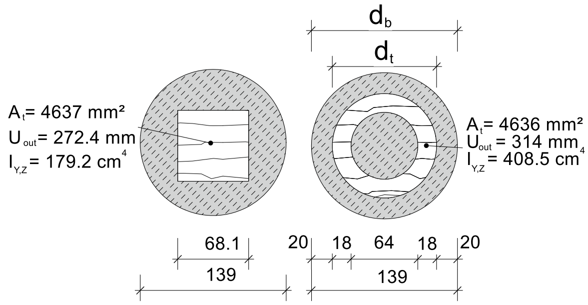


Figure 3: Cross-section of a cement-grouted bore hole with rectangular reinforcement member (left) and a circular hollow section member (right); all dimensions in millimeters

CLHS tensile and bending properties were determined on small and clear specimens and has been described in Hirschmüller et al. 2016, Hirschmüller et al. 2018b and Hirschmüller 2019. This part of the research work has been done primarily to investigate the influence of veneer thickness and curvature on LVL material properties and to define a proper CLHS layer structure. But for the definition of design values testing of structural sized members is inevitable, as brittle material strength is strongly influenced by a volume size effect, mainly caused by a higher probability of strength-reducing wood defects appearing in a larger material volume. Current soil nailing design methods based on limit equilibrium considerations mainly align tensile forces with the nail, wherefore the research focus was inter alia on the determination of CLHS tensile properties in structural dimensions. Temporary soil nailing walls with heights H_S up to about 6 to 7 m cover a large range of typically-practised geometries resulting in a nail length L_N not exceeding 6 m (corresponding to a guide value of ~ 0,8 H_S). Industrially-produced rotary cut veneers are available in lengths up to 3 m and therefore limit the length of available continous CLHS without joints. Thus reliable and efficient longitudinal CLHS jointing without a significant cross-section reduction is a crucial factor for CLHS production of the required lengths. Various concepts have been suggested in the literature to produce long CLHS sections. Hara et al. 1994 used long veneer stripes, which were longitudinally connected by finger joints of the single veneers, for the production of moulded 1/6 round LVL. The moulded LVL were and connected in a high frequency heating press, suggesting a continuous roll forming process (as presented 14 years later in Srinivasan et al. 2008) for the production of long structural elements. Hata et al. 2001 proposed “spiral-winding” of veneer strips wrapped around a mandrel in an interlocking pattern for endless pole production. Gilbert et al. 2017 investigated three longitudinal jointing approaches of CLHS sections and compared the bending capacity, determined in four point bending tests, to reference sections without joints. The authors varied the longitudinal joint by

- inserting a sleeve at the inner CLHS wall with a bending stiffness and bending capacity similar to the continuous CLHS, resulting in a bending capacity of 50% relative to the reference section
- wrapping fibre-reinforced polymere around the longitudinal CLHS butt joint (94% bending capacity)
- longitudinal staggering of butt jointed veneers within the section in a similar process to that used to construct LVL products (83% bending capacity).

Nevertheless, all presented approaches for the production of longer, veneer based structural profiles are based on material jointing, either of veneers or of layered veneer members. However, finger jointing standardised in European standard EN 15497, is a high-performance jointing method mainly used for the longitudinal connection of timber boards as basic material in glulam processing. Youngquist et al. 1984 applied finger jointing to softwood LVL products and found a competitive method of LVL end jointing. But the finger joints in the LVL resulted in fast dulling of the cutterhead, especially if the finger joints were adjusted parallel to the adhesive plane with glue lines abrasing the cutters at one location on the tool. Biblis und Carino 1993 confirmed the strength influence of finger joint orientation and proposed an orientation perpendicular to the adhesive plane to generate reliable connections. Although these publications indicate that finger jointing is a promising way for a longitudinal softwood LVL-connection, several investigations report a limited loading capacity of finger jointed beech wood lamellas in glued laminated timber (Aicher 2001; Volkmer et al. 2017; Ehrhart et al. 2018). This paper discusses the applicabiltiy of finger jointing on beech wood laminated veneer lumber hollow sections and presents the results of large scaled tensile tests under variaton of the joint arrangement.

2. Materials and methods

2.1. CHLS manufacturing and sampling

The tensile properties of full-sized CLHS with and without finger joints were determined in extensive test series of specimens conditioned in normal climate (NC) at 20°C and 65% relative humidity (RH) until reaching equilibrium moisture content ugl ($u_{gl} \approx 11.3\%$). The 2450 mm long CLHS specimens were made of four layers 3.1 mm thick and 2650 mm rotary cut beech veneers. The veneer basic population consisted of thirty 2650 mm long (in grain direction) and 1320 mm wide veneer sheets of quality class E (European Standard EN 635-2), delivered from a Swiss producer (HESS & Co AG). Subsequently to veneer conditioning in NC until weight constancy, the veneer gross density ρ_N was taken, whereby ρ_N of each CLHS was calculated as average mean of the single veneer layers.

To ensure a uniformly-distributed press stress for the production of circular half-sections with small radii, a three-stage production process has been developed using a fluid-filled fire hose for the press stress application.

1. Veneer preparation: Veneers are wetted on their open side (peeling crack side) for preliminary forming of 3 mm thick veneers to a minimum radius of 30 mm perpendicular to the fibre direction. The fixed form, using perforated PVC tubes, is stored in NC for drying at least until weight constancy of the veneers. Due to this weeting prodedere, small veneer radii generally can be produced without crushing the veneers.
2. Adhesive application: After veneer drying, adhesive is applied on the right side (side with closed peeling cracks, log periphery) of each veneer to bond the circular half-sections, whereby the amount of resin is controlled by weighing.
3. Bonding process of half sections

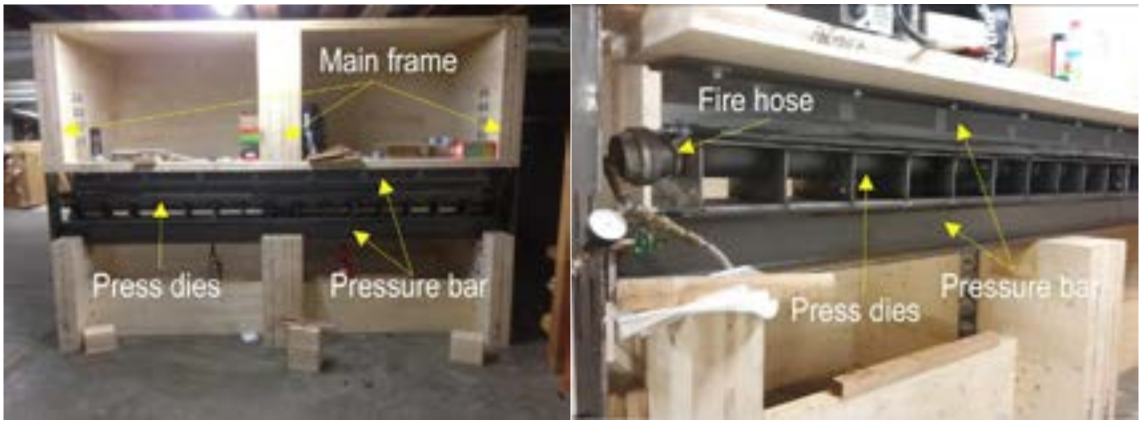
For the production of half-sections, a system with an outer hard form and an inner elastic form is used (Figure 4). The outer hard form is made from insulated cast resin or steel and the inner elastic form consists of a 75 mm diameter fire hose with caps on both ends and connectors for compressed water. The use of an outer steel mould enabled the production of dimensionally consistent half-sections. Depending on the compressor unit and the bursting pressure of the fire hose, not more than 1.0 MPa radial press stress is applied. The fire hose is filled with water at 65°C and the outer cast resin form can be heated with externally-applied heating pads during the adhesive curing process. Thus, bonding at elevated temperatures of at least 30°C is ensured and controlled by a temperature sensor integrated within the cast resin form.

(a) Prototype of a pressing system with elastic fire hose and outer insulated cast resin form

(b) Pressing system with steel moulded outer part

Figure 4: Compression moulding with optimum radial press stress

Subsequently the CLHS is formed by butt jointing the two matched and planed half-sections. For the production of longer CLHS, as demanded for the use in reinforced soil walls ($L_N = 0.6 \sim 1.0\ H_S$), a prototype press was developed. The prototype press (Figure 5) is designed in C-shape for a manual loading from the front side. The main frame consists of four 160 mm thick C-shaped cross laminated timber (CLT) elements with an upper and lower pressure bar (HEB 160-S 235) placed in the recess of the CLT elements.



(a) Front view (b) Detailed view of the press dies

Figure 5: Prototype press

The steel moulded rigid outer part in the form of a half-pipe is placed on the bottom height-adjustable pressure bar, which is lowered during the material loading. After placing the adhesive wetted veneers in the rigid outer form (Figure 4b), the bottom pressure bar is raised until the fluid filled fire hose makes contact with the veneers. A hydraulic inflation system connected to the end caps of the fire hose generates the final press force. After the demanded adhesive curing time of at least 105 min, the half-sections are removed and equalised in a planing unit. To reach at least 30°C core temperature of the veneer layers, the fire hose is filled with water at 65°C. Additionally, 15 heating pads of 65 [W] capacity each are externally applied to the press dies in every single field (Figure 5b) and generate 65°C surface temperature for the acceleration of the MUF adhesive curing process. Subsequently, the equalised half-sections are butt jointed in a similar process and complete CLHS are formed (Figure 6).

Figure 6: CLHS prototype

Specimen geometry and clamping construction (Figure 7) was developed in several preliminary tests correlating the CLHS tensile loading capacity to the clamping system. For CLHS bonding (veneer surface bonding and butt-jointing) melamine formaldehyde resin (BASF Kauramin® 683 with Kauramin® 688 hardener) was used. Two additional 2 mm thick and 400 mm long veneers at the tube interior and six layers 1 mm thick and 600 mm long carbon fibre (FRP) reinforcement (one layer axially and five layers tangentially oriented) prevented the clamping section from splitting due to the high tangential forces caused by the wedge clamping system (Figure 8).

Figure 7: Longitudinal cut of the full-sized CLHS test setup including the wedge clamping construction

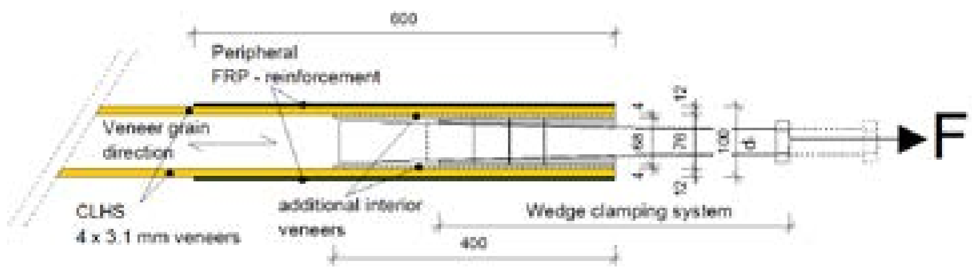


Figure 8: Clamping detail

Besides four CLHS for clamping system verification and estimation of the maximum load $F_{max,est}$, a further 20 CLHS (nominal outer diameter d_t = 100 mm and nominal inner diamter d_i = 75 mm) with 1250 mm free testing length between the FRP reinforcement were produced. Half of the produced samples were used for tensile testing of continuous CLHS without longitudinal joints (batch “CLHS”). The rest were used for the investigation of finger-jointed CLHS with a longitudinal joint. One additionally manunfactured half section, produced from randomly-chosen veneer sheets of the same basic population, was cut into stripes and formed to 48 small bone-shaped specimens (batch “Bone”). This geometry is similar as described in Hirschmüller et al. 2016, Hirschmüller et al. 2018b or Hirschmüller et al. 2018a and was used to test tension strength after NC conditioning. The full-sized CLHS tensile tests (Figure 9) were performed compliant with European Standard EN 408 at *Technische Versuchs- und Forschungsanstalt der Universität Innsbruck* in a specially-developed steel frame using a 1 MN servohydraulic testing machine. The load was increased displacement controlled at 2 mm/s displacement rate, leading to testing cycles of 10 min per test. The application of higher displacement rates was not possible due to rough jerks occuring within the wedge clamping system. This resulted in a machine stroke up to 250 mm during loading, caused by slipping between the wedge clamping system´s cone and chucks. Three continuous samples without joints (batch “CLHS”) had to be adjusted during the tests as the maximum machine stroke of 250 mm was reached. The longitudinal strain was measured at the free tesing length´s mid-section using two symmetrically-installed linear inductive displacement sensors with a measuring length of 500 mm. It were manually removed after a loading level of approximatelly 50% $F_{max,est}$. Each sensor placed upon a half section was positioned perpendicular to the butt joint for the evaluation of sample curvature during testing, due to possible different stiffnesses between the two half sections.

Figure 9: Test setup of a full-sized CLHS

2.2. CLHS FINGER JOINTING

The finger joints (FJ) were manufactured at a local glulam producer (*Grossman Bau GmbH&CoKG, Rosenheim, Germany*) using a common 15 mm finger-jointing profile (I 15/3.8; pitch = 3.8 mm, tip width 0.42 mm, 15 mm finger length and cross-section reduction factor ν = 0.11) at a pressure level of 11 MPa. The adhesive used was of melamine type (BASF Kauramin® 683 with Kauramin® 688 hardener) and applied manually not later than six hours after cutting the fingers. For the jointing of curved geometries a special clamping model was developed to avoid CLHS crushing during the installation´s clamping process. Two different FJ arrangements were produced, one to mimic a staggered arrangement of FJ within the CLHS section (batch "HFJ") and one with fully finger-jointed CLHS across the complete CLHS cross-section (batch "FFJ"). For the production of HFJ series, in a first step 2500 mm long half-poles were produced, cut into two pieces of equal length, and subsequently jointed again to a half-pole consisting of one finger joint in the mid-section of the free testing length.

Figure 10: Half section with milled finger cuts

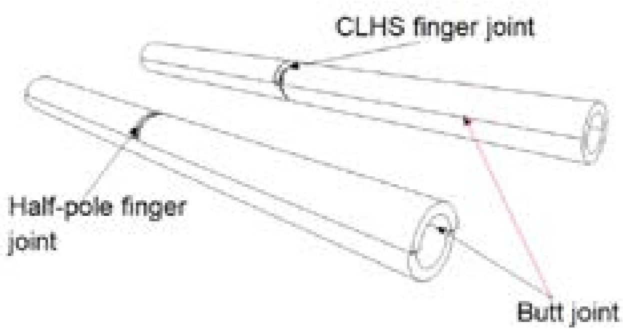


Figure 10: Schematic drawing of a half-pole finger joint HFJ (left) and finger jointing of the complete CLHS cross-section FFJ (right)

Therby the finger edges were oriented parallel to the longitudinal CLHS butt joint (**Error! Reference source not found.**). After one hour of adhesive curing, the finger-jointed half-poles were equalised in a planning unit and butt jointed to continuous half-poles to form a complete CLHS (Figure 10).
FFJ series were produced similarly to HFJ series by cutting the CLHS in half, and the two halves were connected back together with finger jointing of the complete cross-section.

Figure 11: Half-pole finger joint HFJ (left) and complete cross-sectional finger joint (right)

After CLHS production and clamping section reinforcement, the finger jointed specimens were conditioned for two months at NC before testing. In total, ten continous and ten longitudinally-jointed CLHS were produced, whereby five were half-section jointed (Figure 11 left) and five had a complete cross-sectional joint (Figure 11 right). One FFJ member failed during the installation, thus a number n of ten CLHS, five HFJ and four FFJ were tested in total.

3. Results and discussion

The tensile strength f_t of the samples is calculated using equation (1):

$$f_t = \frac{4 \cdot F_{max}}{\pi \cdot (d_t^2 - d_i^2)} \tag{1}$$

The modulus of elasitcity MOE was determined by an averaged strain measurment of the displacement sensors placed in the mid-section of the sample with a linear regression analysis of the stress–strain diagram, with a correlation coefficient of $R > 0.99$ equation (2).

$$MOE = \frac{4 \cdot \Delta F}{\pi \cdot (d_t^2 - d_i^2) \cdot \Delta\varepsilon} \tag{2}$$

In a first step, the force-sensor displacement diagram (Figure 13) was evaluated for differences in sensor elongation. A slight curvature during testing was expected due to the reduced cross-section area of the jointed half section ($\nu = 0.11$) resulting in a differential axial stiffness between the components. But no significant difference in sample curvature between the three structural sized series evaluated was determined. The maximum observed differential strain of $\Delta\varepsilon = 0.9‰$ in batch HFJ was similar to the corresponding series FFJ and CLHS, and therefore the curvature was rather determined by different material stiffnesses of the butt-jointed half-poles. For simplification, the tensile results were applied to the full CLHS cross-section, neglecting the cross-section reduction factor ($\nu = 0.11$) of the finger joints.

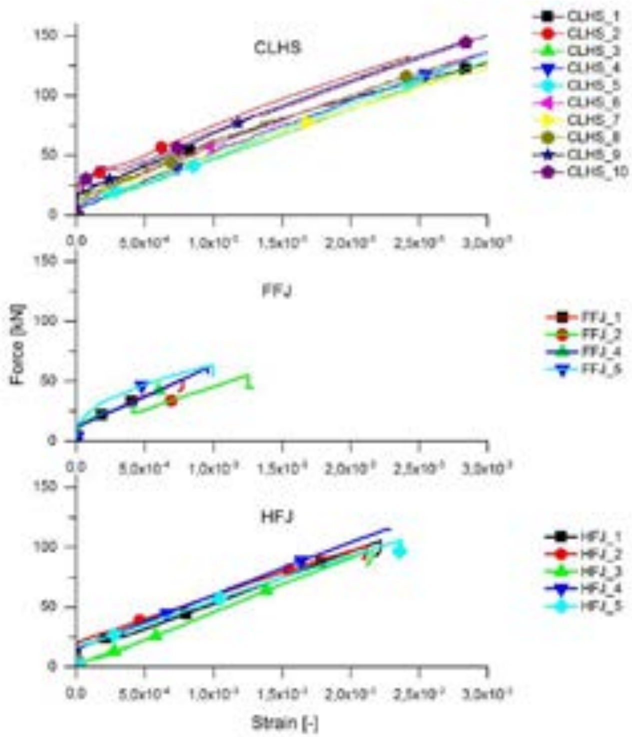


Figure 12: Force-strain diagram of finger jointed structural sized members (FFJ/HFJ) and continuous members without joints (CLHS); strain calculated as average between sensor 1 and sensor 2

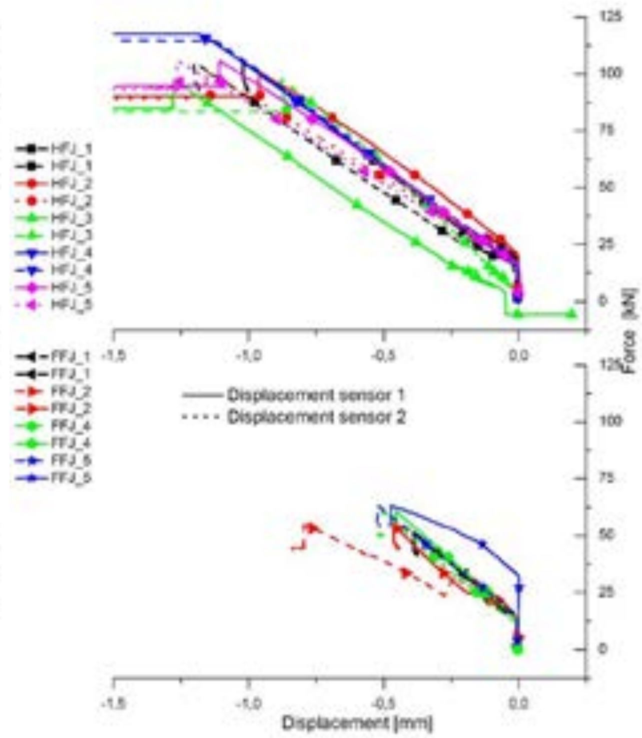


Figure 13: Force-sensor displacement (elongation is plotted with negative values) diagram of *FFJ* fully finger jointed CLHS and members with finger jointed half sections HFJ; *solid line* displacement sensor 1, *dotted line* displacement sensor 2

Due to the high-grade veneers being almost free of defects, the tensile results show a high characteristic tensile strength $f_{t,k}$ of the structural sized CLHS sections without a longitudinal joint (

Table 1). Hereby moderate scattering values (coefficient of variation COV = 10%) were given. Nevertheless, the results obtained of the control batch “Bone”, consisiting of n = 48 small sized and clear specimens are in accordance with published values of beech single veneer tensile properties (Buchelt und Pfriem 2011).

A comparison of the normal or lognormal distributed mean strengths $\bar{x}$ of full finger-jointed members FFJ and sectional-jointed members HFJ by a t-test for two independent samples (including a Welch correction factor in case of unequal variances) at a level of significance of $\alpha = 0.05$ revealed no significant difference in means between both jointing arrangements. However, the low test power (P = 0.11) obtained allows no statistically-sufficient assessment of the results (hypothetical sample size n > 80 for a test power P ≥ 0.7, as Sachs 1993 demanded). This has also been reflected in a low characteristic tensile strength of batch FFJ ($f_{t,k}$ = 27 MPa) due to the low number of tested samples (n = 4), in combination with a remarkable standard deviation (SD = 10.30 MPa).

Table 1: Tensile test results of structural sized series CLHS, HFJ and FFJ, compared to results of small, clear specimens (Bone) and literature values LIT 1 (Buchelt und Pfriem 2011), LIT 2 (Pollmeier Massivholz GmbH&CoKG 2018)

Group \ Parameter	Test	n	$\bar{x}$ [MPa]	SD [MPa]	COV [%]	$\tilde{x}$ [MPa]	$f_{t,k}$ [MPa]	u_{gl} [%]	ρ_N [kg/m³]
CLHS	f_t	10	86.77	9.05	10	86.04	69	11.8	677
	MOE	10	12393	1053	8	12513	--	11.8	
HFJ	f_t	5	54.82	6.76	12	56.79	39	11.4	649
	MOE	5	12669	994	14	13016	--	11.4	
FFJ	f_t	4	49.80	10.30	21	51.83	27	11.5	719
	MOE	4	13677	1905	8	13938	--	11.5	
Bone	f_t	48	98.39	16.21	16	98.20	71	11.1	--
	MOE	48	12692	770	6	12832	--	11.1	
LIT 1	f_t	*80*	*99.6*	*24.9*	*25*	--	--	--	--
	MOE	*80*	*12963*	*1687*	*13*	--	--	--	
LIT 2	f_t	--	--	--	--	--	*60*	--	*800*
	MOE	--	*16800*	--	--	--	*14900*	--	

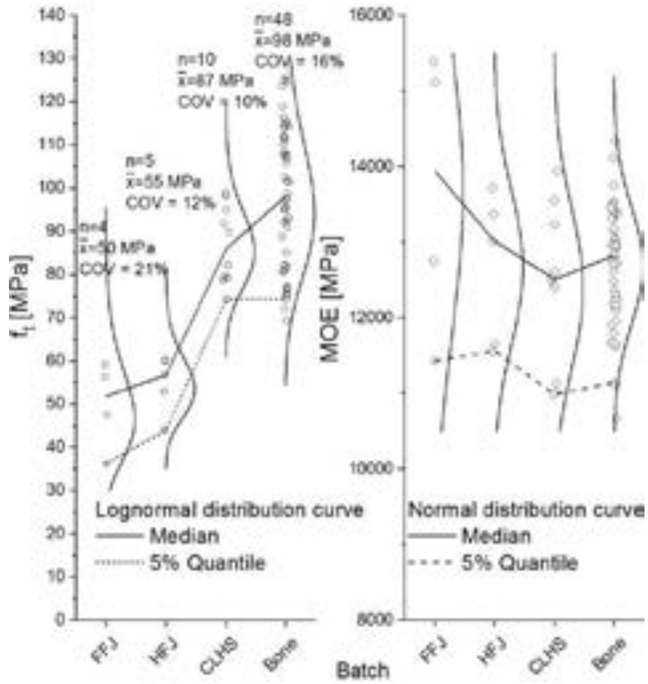


Figure 14: Scatter diagram of f_t (left) and MOE (right), comparing series FFJ, HFJ, CLHS and Bone

Similar to findings in small, clear specimens presented in Hirschmüller et al. 2018b, only a poor correlation was found between the common strength grading criteria MOE and f_t, and almost no correlation between ρ_N and f_t and MOE respectively (Figure 15). This findings emphasise the need for improved grading parameters for beech LVL, including a reliable determination of the veneer grain deviation as extensively described in (Ravenshorst 2015). The failure mechanism of jointed samples was determined by the reduced cross-section at the joint as expected. In all HFJ samples cracks initially occurred at the finger tip, leading to a brittle tensile failure of the jointed half section. After following a crack path along the butt joint, the complementary half section (without joint) failed at the weakest link in a short fibred fracture pattern typical for beech (Figure 16 left).

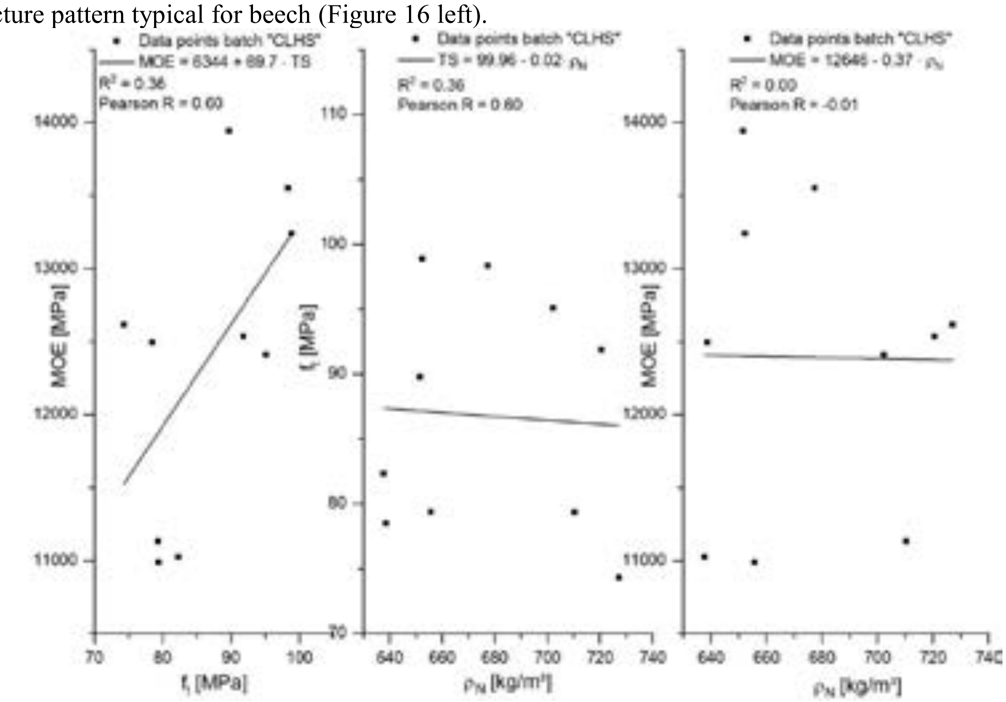


Figure 15: Correlation between f_t and MOE (left) and f_t and ρ_N (centre) and MOE and ρ_N (right) of batch “CLHS”

All FFJ samples failed at the finger joint, revealing a tensile failure at the finger tip or a shear failure at the finger sides, but always with fracture in the timber member (Figure 16 right). Just one member already failed during the clamping works due to an insufficient bond (FFJ_3) and had to be removed from further evaluation as no results could be obtained.

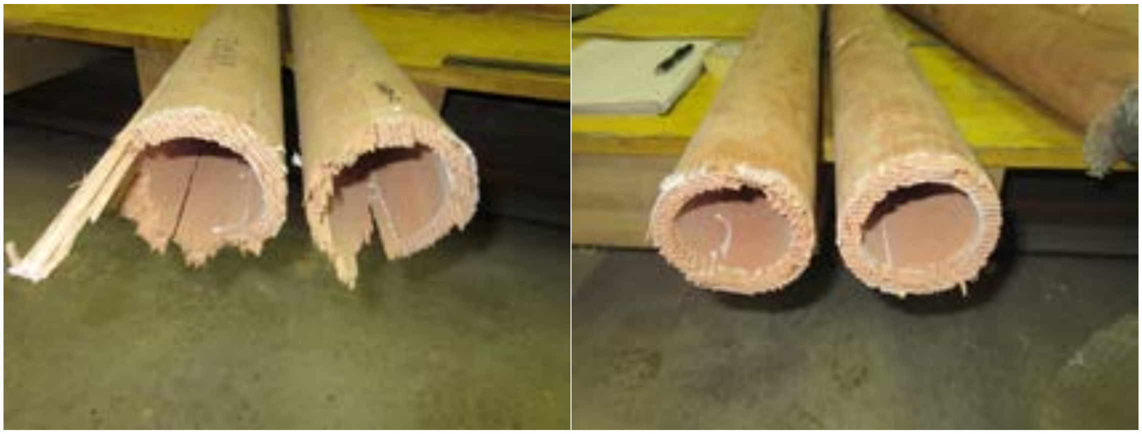


Figure 16: Exemplary fracture patterns of HFJ series (left) and FFJ series (right)

6. Summary

However, NC conditioned beech CLHS achieve superior tensile properties, independent of the curved profile geometry. Finger jointing as an efficient and industrially well-established method of connecting plane timber members is also applicable for curved, layered veneer structures, although the abrasive bond lines require cutterhead modifications to achieve a service life similar to applications in solid timber elements. Despite a larger cross-section reduction of full finger-jointed sections, the difference in mean strength between FFJ sections (43% strength reduction compared to reference CLHS) and HFJ sections (37% strength reduction) is marginal, but still has to be improved and evaluated in further research. In half of the FFJ samples a shear failure on the finger sides was observed, resulting in lower strength, larger scattering and thus a low calculated characteristical strength.
In summary, based on the data presented it can be stated that

- even at a level of significance $\alpha = 1\%$ neither normal and lognormal nor Weibull distribution of f_t and MOE in batch CLHS could be rejected,
- no correlation was found between MOE (f_t) and $\rho_{N,}$
- MOE and f_t correlate poorly positively and
- finger jointing is a promising alternative to staggered veneers for the production of curved and structural sized endless CLHS.

Acknowledgements

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