Innovative beams, floors and floor connections made of hybrid timber structures

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1. Introduction

The use of quasi-homogeneous materials and hereof made structures can often be technically and economically the best solution. However, when looking at the upper end of structural strength and stiffness performance as well as at high strength-weight ratios homogeneously built-up structures are in general uneconomic as wasting much costly materials being strongly underutilized in distinct cross-sectional areas. Combining different strength grades of the same material source is obviously highly advantageous. So, in case of wood an inhomogeneous glulam (GLT) built-up with high-strength laminations in the outer parts of cross-sectional depth and lower-grade laminations in the centre part is preferable in most cases with regard to a proper material utilization and costs. However, an inhomogeneous build-up being confined to the same intrinsic class of material, say solid wood laminations from softwoods, shows obviously performance limits which e.g. in case of GLT according to EN 14080 [1] is a GL32c.

A smart and successful option to extend the performance limits of mono-material build-ups consists in the combination of different materials to create hybrid elements and structures. In case of wooden compounds this means the combination of softwoods and hardwoods and in addition the substitution of solid wood by engineered wood materials such as laminated veneer lumber (LVL) or OSB and plywood in case of web components. This paper presents a compilation of some innovative high-performant hybrid beams, floor or roof elements, floor to floor and floor-column connections co-developed and assisted for approval by German and European building authorities at Timber Department of MPA University of Stuttgart in the last decade.

2. Hybrid Glulam Beams

2.1. Horizontally staggered build-ups

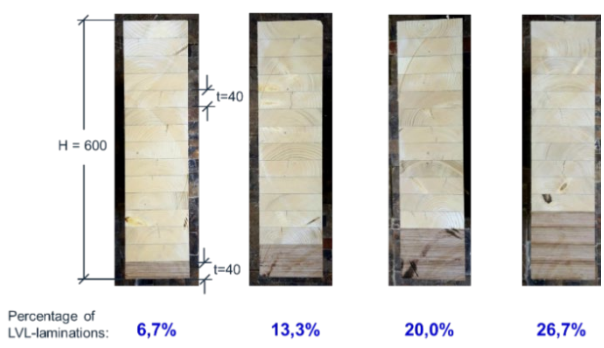
Glulam build-ups made from softwoods as defined in the European harmonized product standard EN 14080 are restricted to a single species, e.g. spruce (picea abies) or Scots pine (pinus sylvestris). The highest GLT strength class of GL32 (h or c) requires a tensile strength class of T26 representing the upper end of machine strength graded softwood boards. Conversely the tensile strength of LVL laminations made from soft- or hardwoods extends much higher. The characteristic tensile strength of spruce and pine LVL is 35 N/mm² and 37 N/mm² ([2], [3], [4]),respectively, and for beech and birch LVL tensile strength is up to 60 N/mm² [5].

Hence the placement of these high-strength materials at the outer edges of a GLT cross-section is evidently rewarding [10]. An exclusive use of the reinforcement at the bending tension edge is in many cases economically preferable, hereby activating a plastic compression block of the lower-strength softwood laminations. Such build-ups have been successfully tested in an MPA research project ([6], [7], [8], [9]) laying the basis of a European Assessment Document (EAD 130740-00-0304 [11]) and a first issued German Technical Approval Z-9.1-910 [12].

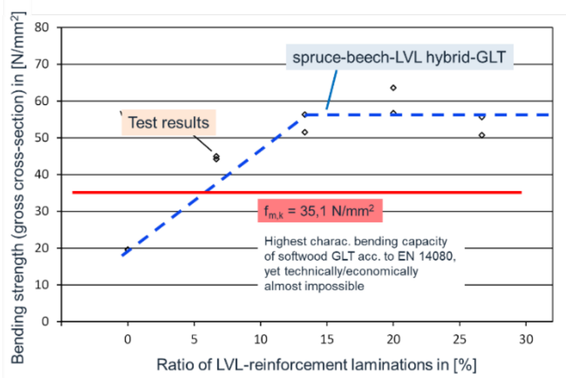
The bending capacity gains vs. a homogeneously or inhomogeneous built-up mono-material GLT depend obviously on the relative portion of high strength laminations at the edges of the cross-sectional build-up (Fig. 1a) which vice versa then triggers the size of the plastic domain of the bending compression edge. It can be seen that the capacity of the bending member is entirely triggered by the quasi-plastic and damage-softening compressive behaviour [13] of the softwood laminations. Fig. 1 b highlights the bending capacity increase depending on different beech LVL reinforcement ratios at the bending tension edge. Figs. 1 c and d reveal the damage features at the bending compression edge in case of beech LVL reinforcement at the bending tension edge with two or four laminations, representing reinforcement / substitution ratios of 13,3% and 26,7% with regard to the full cross-section.

The shown fracture appearances, being entirely different from those with mono-material softwood GLTs visualize articulate crushing and buckling of the axially compressed softwood laminations in the upper cross-section part. It can also be seen that the size of the compressively damaged cross-sectional depth is much larger in case of a (too) high reinforcement ratio of 27% (Fig. 1 d) as compared to a lower ratio (13%) shown in Fig. 1 c. It is revealed that reinforcement by beech LVL-laminations with one-sided cross-sectional fractions of 7% and 13%, respectively, enable GLT bending strengths of about 40-50 N/mm² being 25% to 60% higher as compared to the highest mono-material softwood GLT strength class GL32 acc. to EN 14080.

It should be stated that the outlined extreme bending strength gains obtained with beech LVL laminations are evidently significantly smaller in case of reinforcement by softwood LVL laminations. Nevertheless, also in this case it is possible and building regulatory approved (Z-9.1-910 [12]) that the characteristic bending strength of a GL24 made from solid softwood laminations can be upgraded by 26% to a «GL30,3» by a one-sided 20% reinforcement with spruce LVL laminations.



a)



b)

c)

d)

Figure 1 a–d: Hybrid glulam build-up of softwood GLT reinforced at the bending tension edge by beech LVL laminations investigated reinforcement ratios

b) bending strengths depending on reinforcement ratios

c, d) damage features in the cross-sectional bending compression part depending on reinforcement ratios (13,3% and 26,7%, respectively)

2.2. Vertically staggered build-ups

The placement of openings, rectangular or circular is in many constructions an inevitable architectural and technical necessity to enable the passageway for eg. ventilation and (sewage) water pipes. However, this demand poses a massive problem for softwood glulam beams as the opening provokes at the corners of rectangular holes and similarly at distinct locations at the periphery of round holes high tensile stress concentrations perpendicular to the grain i.e. in the utmost weakest direction of wood (Fig. 2). These stresses can be compensated with internal reinforcement by self-tapping screws or glued-in steel rods or by external reinforcement with laterally glued-on plywood plates. These options are specified in DIN EN 1995-1-1/NA [14] and the new draft of Eurocode 5 (prEN 1995-1-1 [15]). However, internal rod and external panel reinforcement are subject to limited hole sizes. Further, lateral reinforcement has a strongly declining effect in case of larger beam widths as the constraints executed by the lateral panels have limited stress spread towards the inner part of beam width [16].

To overcome the drawbacks of the mentioned reinforcements a hybrid GLT beam build-up with vertically arranged interior layers of cross-banded high-strength beech LVL has proven to be highly efficient. Figs. 3a and b show the cross-sectional build-up of an internally LVL plate-reinforced softwood GLT beam as developed, designed and tested by Hess Timber, Lendlease Designmake and MPA for the International House Sidney, Australia [17], [18], [19].

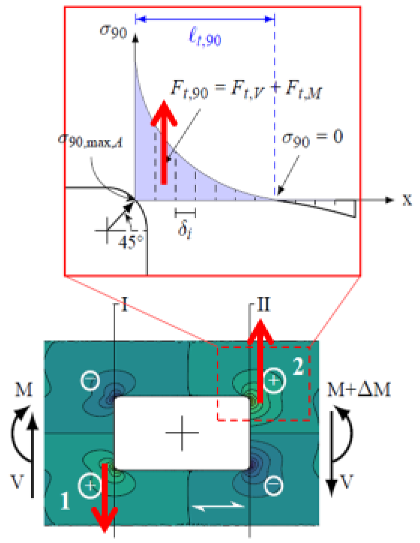
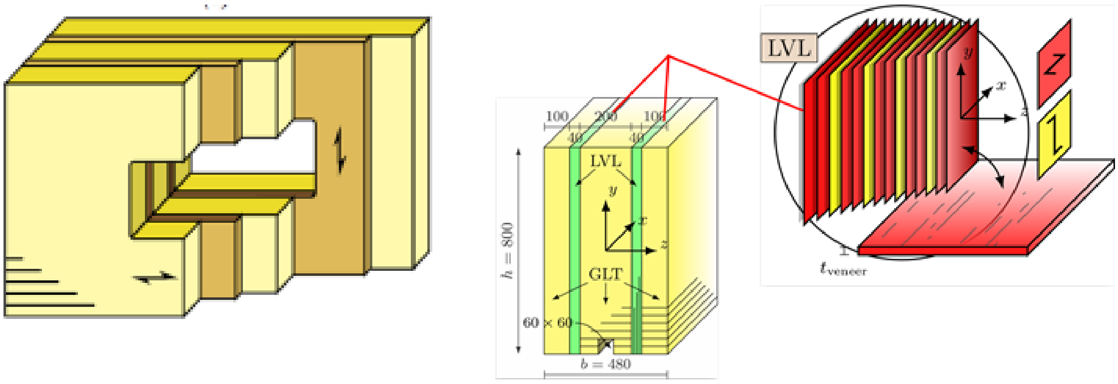


Figure 2: Damage relevant tensile stresses and resultant forces at the corners of rectangular holes in (GLT) beams loaded in bending

In the specific case two tailor made LVL plates are arranged in-between of three adjacent softwood GLT beams of strength class GL28. The beech wood LVL consists of 10 LVL plies with fiber direction parallel to the beam axis and 4 plies orthogonal. The latter plies and the hereby generated strength and stiffness normal to beam axis act as the actual reinforcement for the detrimental tensile stresses perpendicular to GLT fiber axis. The ratio of the characteristic tensile strengths perpendicular to fiber direction and beam axis of the beech LVL and spruce GLT material amount to $f_{t,90,k,LVL}/f_{t,90,k,GLT}$ =.34. On the other hand, the well balanced ratio of moduli of elasticity $E_{0,mean,LVL}/E_{0,mean,GLT}$ =0,94 ensures a rather homogeneous distribution of normal and shear stresses in beam length axis.



a)

b)

Figure 3 a, b: Internal reinforcement of softwood GLT beams by internal vertically arranged beech LVL plates

a) schematic view

b) cross-sectional build-up and dimensions

ip and Figure 4: View of large rectangular holes with internal beech LVL reinforcement plates at the International House Sydney

Figure 4 reveals some of the large internally reinforced openings with a hole to beam depth ratio of 0,4 and very small inter-hole distances of 0,63 between adjacent vertical hole edges as realized at the International House Sydney [19].

Full scale tests with the shown hybrid cross-sectional build-up and hole configurations proved a damage tolerant, non-brittle fracture behaviour of the beams, contrary to that normally observed for glulam beams with holes. The ultimate load of the novel build-up was/is not induced by the stress concentrations at the corners of the holes. The obtained bending stiffness and capacity of the highly perforated beam is almost equal to that of a pure GL 28 of same gross cross-section without holes.

The presented technically and architecturally pleasant looking hole reinforcement solutions have been implemented in the meanwhile in some more buildings.

2.3. Horizontally and vertically staggered build-ups

Thin webbed I-beams and the more stout I-shaped formwork beams are generally composed of flanges made from either solid softwood or softwood LVL and the web consists of a wood-based panel which may be plywood, solid wood panel, OSB or particle board.

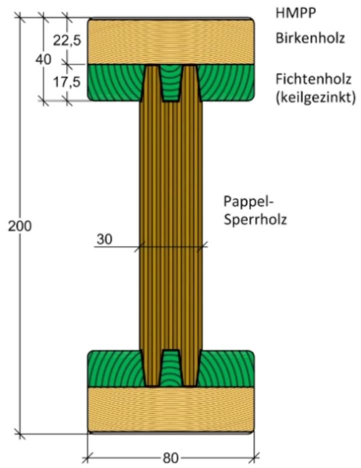
All formwork beams used for RC-shuttering works and conforming to EN 13377 [20] are subject to identic requirements on characteristic section forces irrespective of their partly very different build-up and actual load bearing capacity potential. The reason behind this levelling was / is that formwork beams of different manufacturers may be mingled on the building site and the visual distinction between different brands becomes difficult due to wear after longer service times. However, this approach clearly hinders product progress.

An exception of the stated product levelling has been introduced by the company Doka, Austria, by the so-called I-tec beam covered by a German Technical Assessment Z-9.1-773 [21] where the approval work had been performed at MPA. The cross-sectional build-up of the beam shown in Figs. 5a and b consists of hybrid flanges made from an outer birch lamination glued to an inner spruce lamination while the web is made-up of a 15-layer plywood made from poplar. The reason for the hybrid flange build-up is triggered by two aims, being (i) a higher tensile strength as compared to spruce only and (ii) to achieve much higher compressive and tensile strength perpendicular to fiber in order to avoid flange splitting by the web in the support areas.

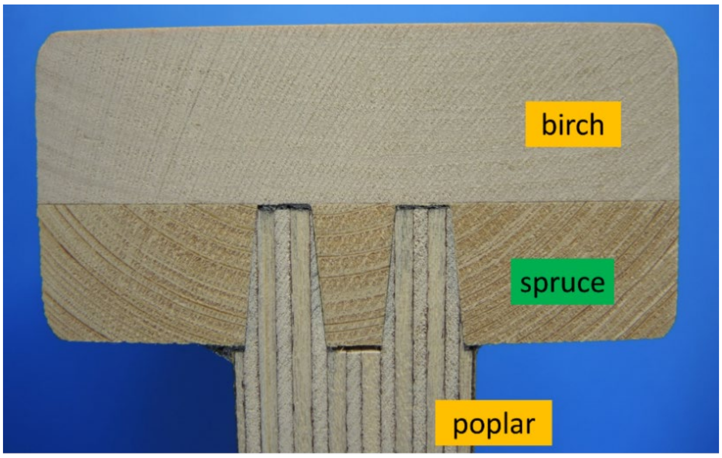
The characteristic moment, shear and support force capacities of the I-tec beam

M_k = 19,5 kNm, V_K= 44,0 kN, $R_{b,k}$ = 86,6 kN

exceed the capacities of the EN 13377 beams by factors of about 2. Further important details are found in [21].



a)



b)

Figure 5 a, b: Hybrid I-tec formwork beam by company Doka, Austria, according to German technical approval Z-9.1-773 [21]

a) cross-sectional build-up and dimensions, b) close-up of hybrid flange-web lay-out

3. Innovative floor and roof elements

Wooden floor and roof elements consist in general either of wooden ribs with one- or both-sided sheathings, hence represent so-called timber frame elements, or are monolithic mono-material slabs made from cross-laminated timber (CLT).

Timber frame-type elements span today almost throughout one-axially in direction of the lengthwise arranged ribs. The wood-based sheathings are prevailingly nailed or screwed to the ribs and to a much lesser extent glued-on. Specific build-ups differ mostly with regard to more or less sophisticated coverings for sound insulation or fire resistance. They are lightweight as compared to much heavier monolithic CLT elements built-up from cross-wise layered and bonded softwood boards. In general, CLT elements today span one-directionally too, what is mainly but not exclusively bound to production and especially transport issues. Hence the width of the elements is maximally about 3,5 m whereas lengths are in general in the range of 8-16 m.

Different from timber-frame elements, CLT panels could easily span bi-axially with rather balanced orthotropic behaviour provided a well-performant joining method of the slabs in the secondary i.e. narrow direction of the elements can be established. This, apart from rare solutions ([22], [23], [24]) represents up to today a widely unsolved timber construction issue. Following, two examples of innovative floor and roof slabs, addressing both element alternatives are presented. Firstly, the build-up and some properties of an extreme lightweight, quasi-timber frame element, the so-called Kielsteg element are outlined, followed by a novel jointing technology for bi-axially spanning CLT plates.

3.1. Hybrid wide-spaning thin-webbed Kielsteg element

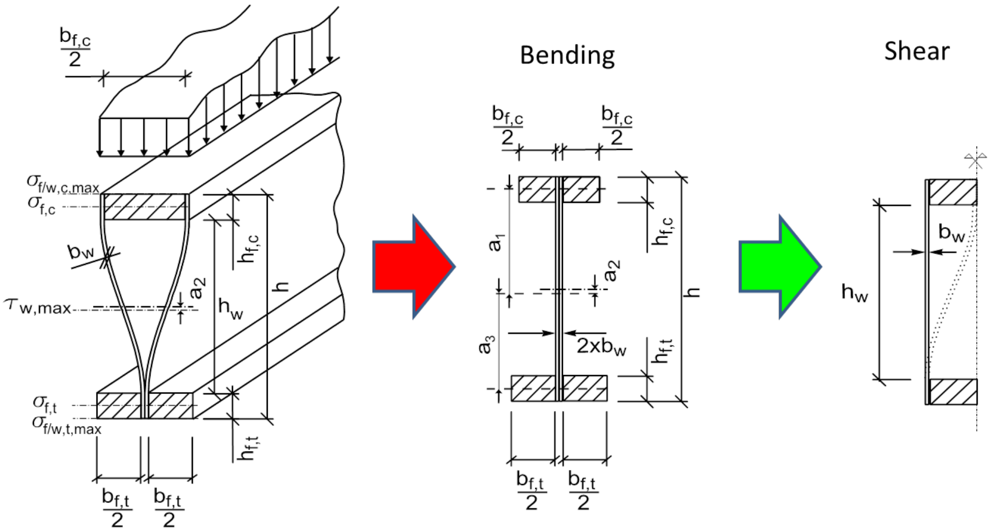
The so-called Kielsteg (engl. Keel web) element represents a bonded both-sided stressed skin element consisting of finger-jointed lumber chords arranged lengthwise in parallel at the cross-sectional bending tension and compression edges. The multiple parallelly arranged webs consist of S-shaped panels of either plywood or OSB depending on cross-sectional element depth (Fig. 6a, b).

Fig 6c shows the representative unit cell of the cross-sectional build-up and geometry simplifications used in the bending moment and shear force design. Regarding the design verification of compressive stresses normal to element plane the S-shaped geometry has to be considered (see below).

The element is produced fully automated with constant widths and lengths of 1,2 m and 32 m, respectively (Fig. 7). The cross-sectional depths range from 220 to 800 mm. A 3-layer plywood with 4,8 mm thickness is used for webs up to element depths of 380 mm. For larger cross-sectional sizes, depending on element depths and structural utilization OSB with thicknesses of 8-12 mm is taken.

a)

b)

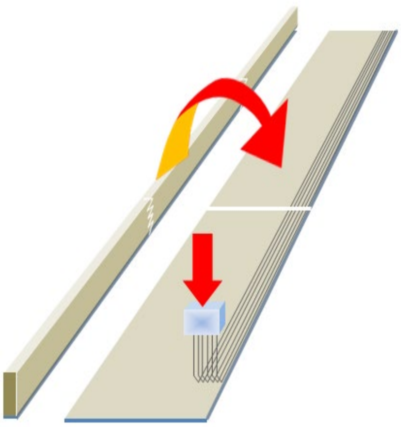


c)

Figure 6 a–c: Kielsteg (Keel web) element acc. To ETA 18/1014 [27]

a), b) View of Kielsteg elements with S-shaped webs made of a) plywood or b) OSB

c) design relevant unit cell of Kielsteg element and geometry simplifications for bending and shear design



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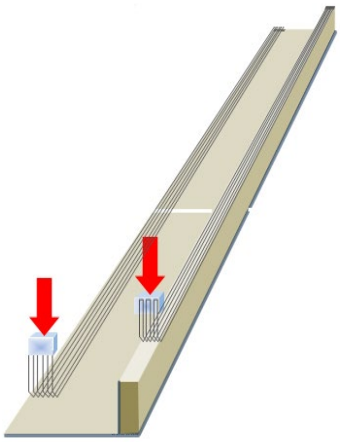

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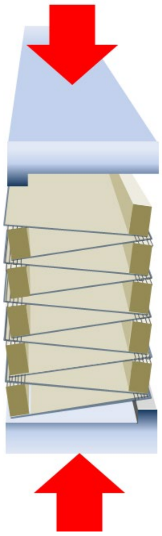


c)

Figure 7 a–c: Basic steps of Kielsteg element manufacture along the fully automated production process at company Kulmer, Austria

a) 1st adhesive application to web panels and positioning of 1st finger jointed lumber flange

b) Simultaneous adhesive spread on web panel and narrow rib edge (not shown: positioning of next web panel layer)

c) Cramping process with possible pre-cambering

The double curvature of the S-shaped webs introduced in the production during the bonding cramping process allows for a superior non-linear bending behaviour of the webs at end and intermediate supports (Fig. 8). Contrary to straight web plates otherwise exclusively used in thin-webbed elements (I-beams), the webs exhibit no distinct stability behavior but instead linear and non-linear bending. The bending stresses perpendicular to element length introduced in the webs in the cramping process, subject to some relaxation, have to be accounted for in the design derived theoretically and experimentally in the approval process at MPA ([25], [26]). The European Technical Assessment ETA 18/1014 [27] of the Kielsteg element produced today exclusively by company Kulmer, Austria, is based on ETAG 019 [28], now EAD 140022-00-0304 [29].

Besides the mere length dimensions rendering the element the world´s longest prefabricated (timber) element (Fig. 9) with a total instalment area of 380.000 m^2, Kielsteg elements are excelled by a superior moment to weight ratio. This feature is highlighted in Table 1 in comparison with monolithic symmetrically built-up CLT elements with board thicknesses of 40 and 45 mm. Firstly, the prevailing cross-sectional CLT depth range for floors of 200 mm to 280 mm is regarded. It can be seen that the characteristic bending capacities of Kielsteg elements are almost equal when compared to CLT of same depths.

However, regarding self-weight, Kielsteg elements are about 50% to 60% lighter as CLT, i.e. weight-normalized Kielsteg elements show roughly a two times higher bending capacity. Regarding cross-sectional depths of 380 mm up to 800 mm, no sensible comparison with CLT can be made as these CLT-thicknesses are not produced. Nevertheless, it is noteworthy to mention with regard to the benefits of lightweight construction that the weight-normalized bending capacity of Kielsteg elements increases roughly proportional to element depth. So, at h = 800mm ratio M_{05}/m_{keel} amounts to 9,2 x 10^6 kNm/kg as compared to 3,4 x 10^6 kNm/kg at h = 230 mm (width: b = 1m).

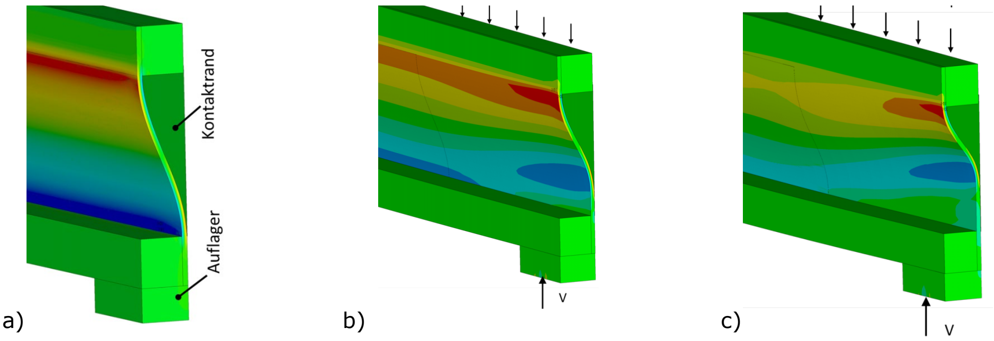


Figure 8: Web bending behaviour due to compressive forces in support area
a) unloaded
b), c) web deformations at 50% and 100% of ultimate load

Figure 9: Mounting of Kielsteg elements with a length of 23 m at a building site.
The also shown elements with shorter lengths enable roof windows

Table 1: Comparison of Kielsteg vs. CLT elements regarding self-weight, moment capacity and moment-weight ratio

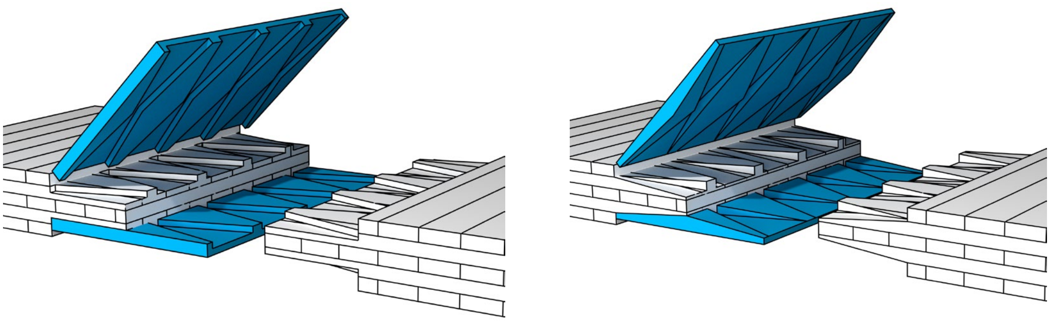
Keel-web elements				**depth-wise corresponding X-Lam elements**					**Moment and weight ratios vs. CLT**	
Height h [mm]	Flange depth h_f [mm]	Weight m_{Keel} [kg/m²]	char. Moment capacity M_{05}/m [10^6 kN]	Height h [mm]	Board depth h_f [mm]	Lay-ers n_{layers} [-]	Weight $m_{X\text{-}Lam}$ [kg/m²]	char. Mo-ment ca-pacity M_{05}/m [10^6 kN]	$\frac{M_{05,Keel}}{M_{05,X-Lam}}$ [-]	$\frac{m_{Keel}}{m_{X-Lam}}$ [-]
228	45	45	154	200	40	5	84	125	1,23	0,54
				225	45	5	94	158	0,98	0,48
280	57	46	236	280	40	7	118	240	0,98	0,39
380	43	47	305	-						
485	57	71	494	-						
800	80	120	1107	-						

3.2. Hybrid edge-connection for the secondary direction of CLT plates

The developed connection ([30], [31]) represents a 3-dimensional extension of the lap jointing method [22] where a wooden gusset plate is bonded on top of the outer board layers oriented in the secondary CLT direction. Doing so, of course the outermost layers spanning in the primary load bearing CLT direction have to be removed in the joint area. The load transfer mechanism of the established connection [22] represents a 1-sided single gusset lap joint whose tension-shear capacity is strongly affected by the superimposed bending moment which originates from the offset (eccentricity e) of the resultant forces in the jointed secondary layer boards and the gusset plate. The novel connection developed at MPA within Stuttgart University´s Cluster of Excellence IntCDC (Integrative Computational Design and Construction for Architecture) aimed to mitigate the mentioned eccentricity drawback. The task was pursued with two somewhat different alternatives A and B shown in Figures 9a and b targeting at

i) a reduction of force eccentricity e by creating bond lines at different depths of the jointed boards,
ii) creating vertical bond lines, too, and
iii) to use a finger joint-type load transfer.

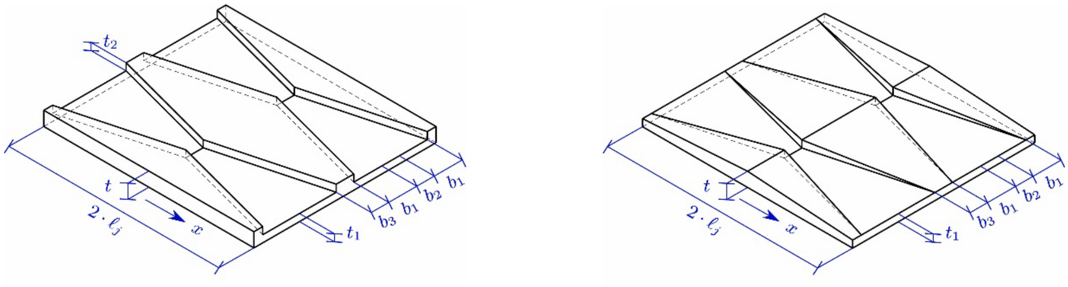
The sketched attempt necessitates evidently a 3-dimensional shaping of the gusset plate and of the jointed CLT board ends with finger joint-like profiles. In case of alternative B the finger joint surface is further tapered on the wide-side in order to reduce the stress concentrations in the joint. The obviously more demanding manufacture of connection alternative B necessitates a milling machine with four degrees of freedom whilst alternative A can be manufactured with commonly available three-axis CNC machines.



a) b)

Figure 10 a, b: Hybrid edge connection for secondary CLT direction with finger-profiled LVL gusset plates
a) Alternative A with horizontal wide finger faces b) Alternative B with tapered wide finger faces

The material used for the gusset plate is slightly cross-banded beech LVL with a total thickness t of 40 mm and the residual depth of the milled recesses being 20 mm thick. Figures 11a and b depict the geometry of the gusset plates; the dimensions are specified in Fig. 11c. The bonding of the joint is performed by screw gluing. The use of a gap-filling adhesive, preferably of a two-component thixotropic PUR as used in the joint development or of an epoxy resin is required, especially with regard to allowance of lesser strict milling and manufacturing tolerance specifications. Figure 12a shows a milled CLT adherend together with a one-sided attached beech LVL gusset plate of joint alternative B with tapered fingers. Fig. 12b depicts the assembly of the joint with adhesive spread on the CLT finger surfaces and the pre-mounted self-tapping partially threaded screws (diameter 6 mm, washer head) used for screw gluing with rather close screw distances.



a) b)

l_j [mm]	b_1 [mm]	b_2 [mm]	b_3 [mm]	t_1 [mm]	t_2 [mm]	t [mm]	n [-]
250	40	40	20	20	20	40	4

c)

Figure 11: Finger profiled beech LVL gusset plates
a), b) Geometries of alternatives A and B with horizontal and tapered wide finger faces
c) Dimensions

Figure 12: Milled CLT adherend with one-sided bonded beech LVL gusset plate with tapered fingers (alternative B)

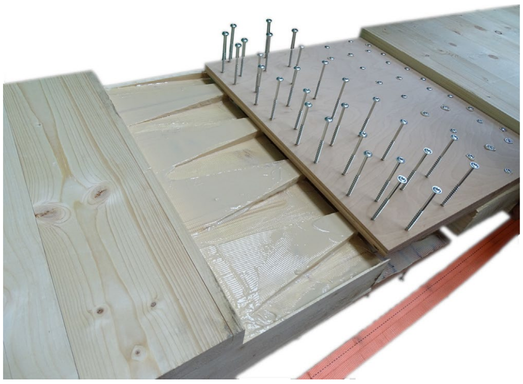


Figure 13: Assembly of developed CLT edge joint with profiled beech LVL gusset plates (here alternative B) showing the adhesive spread and the mounted self-tapping partially threaded screws used for cramping

The experimental investigations with full-sized joints in 5-layered CLT plates of 200 mm depth and 580 m width proofed that the pure bending moment capacity of both joint alternatives conforms roughly to the characteristic capacity of the unjointed CLT plate in the secondary direction. At combined high shear force and moment action the joint capacity exceeds the resistance of the pure CLT and the joint stiffness is significantly higher as compared to pure CLT in the secondary direction. Comparing alternatives A and B, despite a 10% higher moment capacity of alternative B resulting from the depth-wise tapered fingers, alternative A is recommended for practice. This is bound to a much easier manufacturing and hence costs.

In brief it can be stated that the developed jointing method for 5- and 7- layered CLT plates using adhesively fixed finger joint-profiled beech LVL gusset plates allows the manufacture of continuous CLT floors in the secondary direction without strength and stiffness reductions at the joint locations.

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