Production and Technology of Cross Laminated Timber (CLT): A state-of-the-art Report

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Summary

Cross laminated timber (CLT) has been developed into a worldwide well-known and versatile building material. Progressive rates in production volume and distribution can be observed currently. In fact CLT opens new horizons in timber engineering thanks to its laminar structure which makes it well suited for use in constructions of that type which had been subject to mineral building materials like concrete and masonry so far.

After a short introduction this contribution aims on demonstrating current production processes used for rigidly composed CLT. In chapter 2 the process steps are individually described and essential requirements as well as pros and cons of various production techniques are discussed. Latest results of R & D and developments as well as innovations in production technology are presented. In chapter 3 test and monitoring procedures in frame of the internal quality assurance, known as factory production control (FPC), are presented. Thereby diverse regulations as anchored in technical approvals for CLT as well as in the CLT product standard prEN 16351 [1] are discussed. Additionally, some technological aspects of the product CLT together with a comparison of geometrical and production relevant parameters of current technical approvals in Europe are provided in chapter 4.

In the final discussion the main content of production and technology is presented in a condensed way. An outlook in regard to current and future developments as well as concerning the ongoing establishment of the solid construction technique with CLT is given. The product CLT comprises an enormous potential for timber engineering, but also for the overall society. Standardisation and further innovations in production, prefabrication, joining technique, building physics and building construction makes it possible that timber engineering achieves worldwide success.

1. Introduction

Cross laminated timber (CLT) constitutes a plate-like engineered timber product which is optimised for bearing loads in and out of plane. CLT is composed of an uneven number of layers (in general three, five, seven or even more), each consisting of side-by-side placed boards (or beams), which are crosswise arranged to each other normally under an angle of 90° and quasi rigidly connected by adhesive bonding. Due to the continuous bonding and, consequently, the quasi rigid composite action between the single layers, a very compact and versatile product arises. As a consequence, the produced dimensions allow its application in form of large-sized walls, floor elements and other large-sized load-bearing plane-like- as well as linear structural components. In this way, modular dimensions, as known from light-weight wooden constructions (e.g. frame system), can be neglected, due to the fact that window and door openings can be freely placed. This product has opened new dimensions in timber engineering and allows architects and engineers to design and realise monolithic buildings. This is now possible in a manner and dimension which was subject to reinforced concrete, brick or other mineral based building materials. Hence, this product opens up new vistas concerning a new building technique, the so-called “solid timber construction technique with cross laminated timber”, which makes it possible to design and construct with timber in so far unknown dimensions and scales.

The first ideas and development date back roughly two decades. Motivated by a missing market for the side-boards from sawmilling at that time a solid and in regard to swelling and shrinkage in plane direction locked engineered timber product was developed. This locking effect caused by crosswise arrangement of the single layers can be seen as an analogy to the single wood fibre (tracheid) or to a composite of cells. In this way, every wooden cell constitutes a composite of several cell layers winding around the cell lumen in varying crosswise fibre angle and, on their part and in dependency on their function, shows a specific orientation of the cellulose fibres, the primary constituent (total share of 50 ÷ 60 %) in (clear) wood and (structural) timber. Meanwhile, the advantages of this specific orientation between the layers in regard to the load-displacement and failure behaviour of the wooden cell composite but also in analogy with artificial fibre composites have been well described (e.g. [2]; [3]; [4]; [5]). In the broader sense CLT can be also seen as a synergetic product or as further development of historical timber construction techniques of logs or staves, respectively, with their origins in Central and Northern Europe. The combination of both principles to a composite with rigidly bonded crosswise layers constitutes the substantial innovative part of the new solid timber construction technique in CLT (see [6]).

The advantages of CLT as large-sized and panel-like solid timber construction element for the building sector are in particular obvious because of its outstanding degree of pre-fabrication, the dry and clean construction technique and the short erection times on site (e.g. roughly one to two days per family house). The high dimensional stability underlines the fitting accuracy with lowest tolerances, as already well-known for timber constructions in general. The opportunity to transfer the loads two-dimensionally together with its low self-weight, which are both of particular importance and predestine CLT for reconstruction and upgrading of existing buildings (e.g. from Wilhelminian time), but also for resisting exceptional loadings (e.g. earthquakes), are further decisive advantages of this product. In contrast to the light-weight timber structures (e.g. framing, post and beam system), the merits of a clear separation of load-bearing from insulation & installation layers, the low air permeability, the distinctive specific storage capacity for humidity and temperature, the independence of modular dimensions in arranging window and door openings as well as in fastening of furniture have to be outlined as well. The low mass, the stiffness and the bearing capacity of this structural element against in plane and out of plane stresses can be regarded as powerful arguments for its utilisation in multi-storey residential and office buildings, in schools, single family houses, halls and the conversion and upgrading of existing buildings and constructions, but also in wide-span structures like bridges. In particular for wide-span structures rib floors or box beams, as a composite of CLT with linear timber products, like (finger jointed) construction timber, duo or trio beams or glued laminated timber (GLT, glulam), or constructions by means of folded panels are highly advantageous. Not at least because of its versatile applicability, dynamic processes in development and establishment of production capacities with growth rates of 15 ÷ 20 % per year have been observed (see Fig. 1).

These developments have been first realised in Austria and Germany with a current production volume of roughly 500,000 m³/a (2012) and a share of two-thirds of the total worldwide production volume sole in Austria. Worldwide activities in R&D as well as processes for erecting (small & medium) production sites are ongoing and observable.

Although CLT seems to become a mass product on the first view, in reality selling is different from products like GLT and, consequently a production of “standard” CLT elements in stock is unimaginable. In fact, production and selling of CLT conditions a horizontal diversification at the producing industry in terms of incorporating or integrating an engineering department which itself acquires projects and provides technical support for customers (e.g. architects, civil engineers, carpenters and builders). In that sense the production of CLT has to be on commission with batch sizes of ≥ 1. Thus, the processes of cutting and joining have to be directly embedded in the overall production process.

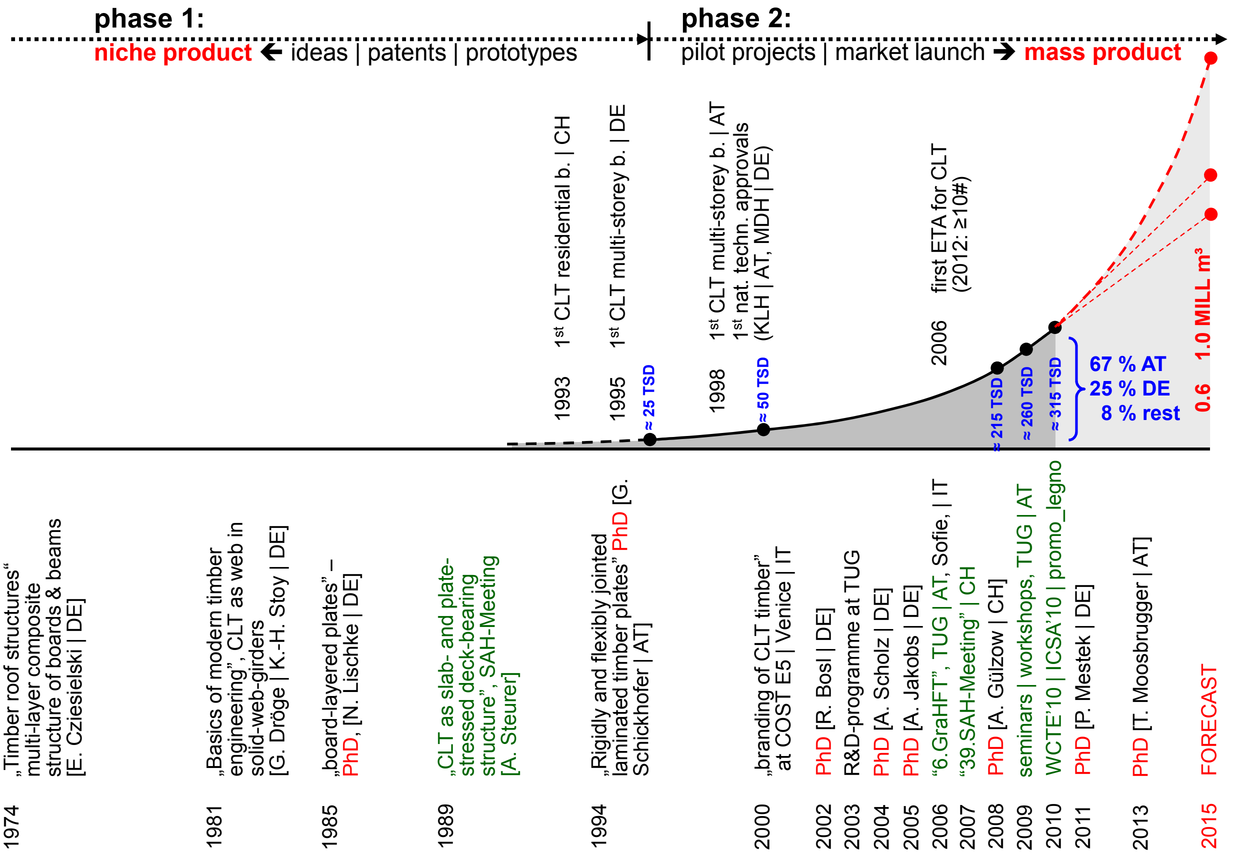


Fig. 1: Development of CLT – timeline ([7]; adapted)

For a maximum and reliable exploitation of CLT’s potential and its worldwide distribution it is required to standardise CLT as much as possible and to extend its production, the design process, handling and joining technology. In that sense international regulations in the frame of standards which comprise all five areas “production & quality assurance”, “testing and evaluation”, “design & verification”, “construction & assembling” and “joining technique” have to be intended; this can be seen as the basis for a reliable distribution and handling of this product, its technology and thus, forms the established solid timber construction technique. Of course, current regulations are primary subject to the individual producers and given in technical approvals, in Europe enforced by the DIBt (Deutsches Institut für Bautechnik, Berlin, Germany), the OIB (Österreichisches Institut für Bautechnik, Vienna, Austria) or as European Technical

Approvals (ETAs), with reference to national or European standards. The developments in standardisation within the last years in Europe, but also in Canada, United States and China allow expectations in regard to a dynamical constitution and a foreseeable launch of required standards.

This contribution aims on the topics "production & quality assurance" and on accompanied data regarding main technological characteristics of CLT. It is intended to give an overview of current productions with focus on the industrial scale as currently mainly established in Europe.

2. Production and processing of CLT: overview and step-by-step

The production process of CLT is in most steps largely comparable with the one of glulam. The relevant steps for producing CLT are shown in Fig. 2.

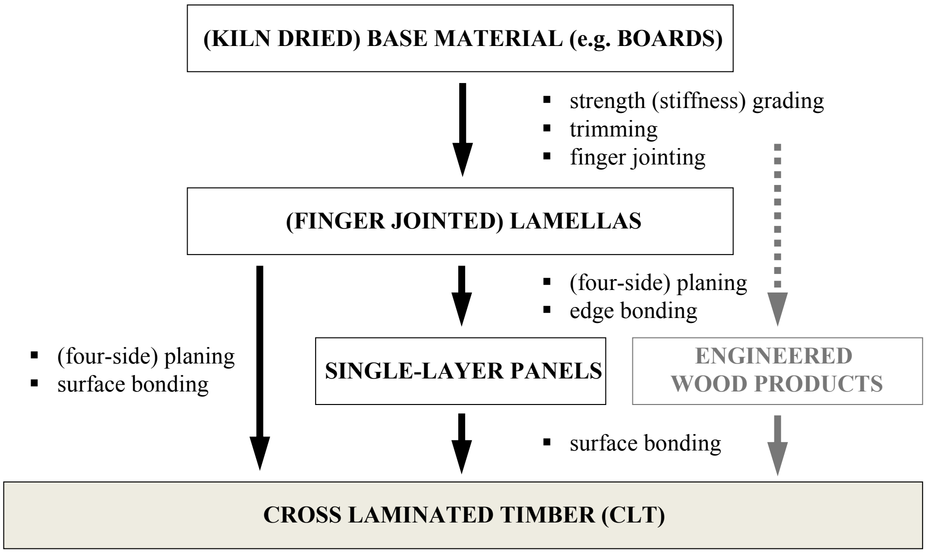


Fig. 2: CLT production process: overview

Basically the production of CLT can be divided into the following steps: (1) strength or stiffness grading of already (kiln) dried boards, (2) cutting out of local growth characteristics which do not meet the requirements of the strength class and finger jointing of the residual board segments to endless lamellas, (3) division and cutting of lamellas for later use in longitudinal and transverse layers of CLT, (4 optional) adhesive bonding of lamellas to single-layer panels, (5) assembling and adhesive bonding of lamellas or single-layer panels to CLT, and (6) cutting and joining to structural elements (customizing). Within the next sections all relevant steps are treated step-by-step and process parameters are discussed.

2.1 Characteristics of raw material and grading process

Normally, CLT is composed of boards with thickness $t_{\mathrm{B}} = (12 \div 45)$ mm (cf. prEN 16351 [1]); following current technical approvals a range of even $(4 \div 80)$ mm, which comprises veneer and beams, is given (cf. Tab. 5). In the context of standardisation and here focusing on construction tenders, a general agreement on standard CLT layer thicknesses with $t_{\mathrm{B}} = (20, 30, 40)$ mm could be achieved in Austria. Further standardisation, in particular with regard to layups of CLT elements optimised for stresses out of plane (e.g. for floors and roofs) and in plane (e.g. for walls), is highly recommended. There is no upper limit for the board width but due to rolling shear stresses in-between the CLT-layers a minimum width of $w_{\mathrm{B}} \geq 4 \cdot t_{\mathrm{B}}$ is recommended and thus anchored in current technical approvals. If this requirement is not kept or the distance between relieves d_R is too short ($d_R < 4 \cdot t_B$), then a reduced resistance in rolling shear has to be considered. Following prEN 16351 [1], the board width is regulated within (40 ÷ 300) mm. In accordance to structural timber, the reference board width is proposed with $w_{B,ref} = 150$ mm, as given in EN 338 [8] and EN 384 [9]. In general, only boards of prismatic cross section are used for CLT. In some cases profiling of the longitudinal edge may be meaningful, e.g. by tongue-and-groove or special types of clearance profiles (e.g. [10]). In this course, the emersion of adhesive is widely prevented and the possibility to create shadow gaps, which come up as consequence of swelling and shrinkage, is included. Furthermore, a higher stability in top layers composed of profiled single boards during pressing is given. Special emphasis has to be put on the assurance that all laminations of the same layer in CLT are of equal thickness. This is to ensure that during surface pressing all zones in CLT are exposed to the same transverse pressure and, consequently, fulfil the requirements concerning maximum gap widths between the boards of different layers. This has to be done in dependency of the used adhesive system, e.g. for one-component polyurethane adhesive the bond line thickness has to be within (0.1 ÷ 0.3) mm.

Currently, mainly softwood species are used for CLT. The main species is Norway spruce (*Picea abies*) in assortment with a small amount of White fir (*Abies alba*). Furthermore, softwood species like Scots pine (*Pinus sylvestris*), European larch (*Larix decidua*), Douglas fir (*Pseudotsuga menziesii*) and Swiss stone pine (*Pinus cembra*) are made use of, whereby the last mentioned species are primary for CLT of high appearance quality and thus are used for the top layers. The worldwide distribution of CLT and of the solid timber construction technique also maintains the application of other species, e.g. of Maritime pine (*Pinus pinaster*) in Sardinia / Italy. The utilisation of hardwood is of course also possible and has already been made, e.g. within the project “massive_living” (three-storey building) in Brucknerstrasse, Graz / Austria where one of in total 22 flats was realized completely with wall elements of CLT composed of silver birch (*Betula pendula*). Further possible species are poplar (*Populus spp.*), ash (*Fraxinus excelsior*) and others which are of economic interest, available in adequate amount in sawmilling qualities and provide a minimum in mechanical properties as required for CLT as structural load-bearing element. On one hand, hardwood species allow to set courses in appearance. On the other hand, the systematic use influences and optimises especially the mechanical potential of CLT. An increase in bending stiffness by means of in shear more rigid transverse layers or top layers of higher bending stiffness (e.g. birch, ash, black locust) is obvious as well as the improvement of the rolling shear resistance of CLT by means of species like birch or poplar for the transverse layers, without increasing the CLT thickness or even by reducing.

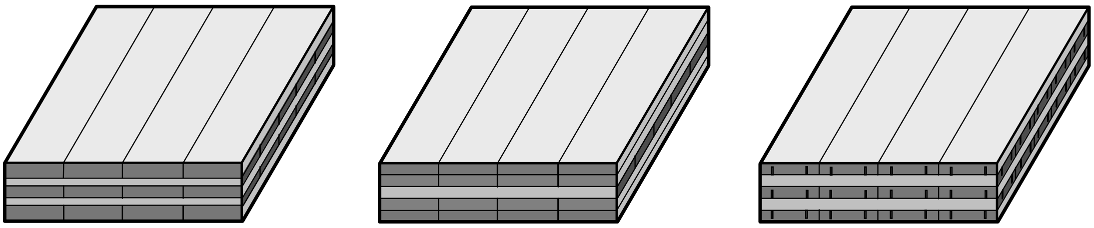


Fig. 3: Five-layered CLT element (schematically): homogeneous, symmetrical layup (left); (multiple) double outer layers (middle); base material with relieves (right)

As required and perhaps in dependency of later additional functions of CLT (e.g. air tightness, higher resistance against rolling shear, acoustic or haptic requirements) it is possible to substitute single layers by laminar engineered timber products, e.g. laminated veneer lumber (LVL), oriented strand board (OSB), plywood or single- or multi-layer solid wood panels. The suitability of the substitute has to be verified, in particular if such a layer is explicitly taken into account in load transfer.

The basic material for CLT is in general technical (kiln) dried and conditioned to a moisture content of $u = (12 \pm 2)\,\%$. Following current technical approvals, a range of even $(8 \div 12)\,\% \pm 2\,\%$ can be found. Next, the material is visually or mechanically graded to strength (stiffness) classes e.g. according to EN 14081-1 [11] or DIN 4074-1 [12]. It is of utmost importance that within a single layer all boards have to be of the same grade. In other cases the grade of the single layer shall be taken as equal to the lowest grade of the used boards. Currently, the strength class system of EN 338 [8] is applied in Europe, although this system has been developed for structural timber which is mainly stressed edgewise in bending. Common strength classes are C24 for a homogeneous layup and, if combined with C16 / C18, for the transverse layers. In fact, the bearing capacity of CLT stressed out of plane in bending is primary governed by the resistance of the top layers in tension parallel to grain. The same situation, a demand-oriented grading, is valid for glulam and, thus, the grading of boards according to requirements in tension parallel to grain is recommended.

According to the glulam standard prEN 14080 [13] the grading in T-classes based on the characteristic 5 %-quantile of strength and characteristic mean of E-modulus in tension parallel to grain is suggested. Following the current technical approvals in Europe the product CLT is primary composed of C24 according to EN 338 [8]. Of course many technical approvals allow a specified amount (i.e. 10 % or 30 % per board layer) of boards dedicated to the next lower strength class without considering the mechanical properties of CLT. It is assumed that this regulation can be traced back to a rough interpretation of tolerances for visual grading given in DIN 4074-1 [12] (section 6.3.2), in which a deviation of ≤ 10 % from grading criteria within ≤ 10 % of the material volume is allowed. There is a strong dissent concerning the statements before the conclusion claiming that generally it would be permissible to mix boards of different grades within one layer ([6]). Although not common today, in some cases, e.g. in case of a CLT floor plate, which is primary stressed in bending, grading the board material rather in stiffness, in conjunction with compliance of minimum requirements of strength, than in strength can be more constructive. In fact CLT elements used in this way have to be rather designed on the subject of serviceability (according the deflection or in cases of longer spans according the vibrations) than in ultimate limit state. This is because of the transverse layers, which make CLT more flexible in shear. Consequently, the optimisation of stiffness is an economical valuable target. Based on several research works which addressed the homogenisation effect as a consequence of the common action of boards in a (quasi) rigid composite (e.g. in glulam), it is well known that the dispersion in strength properties of system products, like GLT or CLT, in comparison to that of their base material is significantly reduced. The homogenisation is even more noticeable and increases with increasing dispersion in strength properties of the base material (board; elements) (see e.g. [14]; [15]; [16]; [5]). Due to the fact that the selectivity in visual grading is usually lower in comparison to mechanical adjustment, a higher dispersion in strength properties of boards is given in general. If these boards (elements) are joined to CLT (system), higher homogenisation effects can be expected (e.g. in resistance against bending stresses out of plane and against tension and compression stresses in plane). Consequently, stiffness grading combined with a method assuring the compliance with minimum requirements of strength (e.g.

by exclusion of specific growth characteristics or by stressing of each board with a predefined proof load) can be a very constructive and economic grading concept.

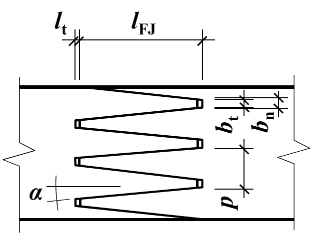
The layup of CLT is in general symmetrical. In cases in which additional layers are applied and rigidly connected (e.g. acoustic panels) in order to keep dimensional stability in some circumstances, it can be advisable to apply a counteracting layer which is in regard to swelling and shrinkage equivalent to the additional layer(s). Normally CLT is composed homogeneously of layers of equal strength properties. A combined but symmetric composition of layers with different strength classes is possible, but requires special consideration in calculating the mechanical properties of this CLT, e.g. by taking into account the rigid composite theory. Some compositions of CLT which are optimised for example for stresses out of plane feature two or more parallel layers than combined top-layers, applied to optimise the performance of CLT's bending stiffness by increasing the moment of inertia (see Fig. 3, middle).

2.2 Production of finger jointed lamellas

Based on longitudinal incremental results as output of strength grading local (discrete) growth characteristics which do not meet the requirements of the strength class are cut out and the remain board segments are joined again by means of finger joints (FJs). Thus finger joints provide an economical approach for joining board segments longitudinally of which discrete sections with a possible negative impact on the target strength distribution of the board sample were removed selectively with the aim that the main part of the original board remains.

The finger joint itself constitutes a self-centring profile representing a folded scarf joint. Thanks to the optimised profile, finger joints enable a simple, fast and form-fit connection between elements by maximising the bond surface and minimising longitudinal losses of board material. For CLT lamellas, profiles which have been already optimised and approved for the production of glulam are used with a finger length of $l_{FJ} = (15, 20)$ mm. For an overview of these profiles and of main geometric parameters see Tab. 1. Of course it is also possible to joint whole CLT elements by means of large finger joints (LFJs) with finger lengths of $l_{FJ} \geq 45$ mm; this is discussed in more detail in section 2.6.

Tab. 1: Finger joint profiles, geometric measures and loss in cross section

l_{FJ} [mm]	p [mm]	b_t [mm]	b_n [mm]	l_t [mm]	α [°]	$v(b_n)$ [%]	
15	3.8	0.42	0.52	0.5	5.6	13.6%	
20	5.0	0.50	0.60	0.5	5.7	12.0%	
20	6.2	1.00	1.11	0.5	6.0	17.8%	
50 [1)]	12.0	2.00	2.48	3.0	4.6	20.7%	

l_{FJ} … finger length; p … pitch; b_t … tip width; b_n … base width; l_t … tip gap; α … flank angle; $v(b_n)$ … loss in cross section

1) recommended profile for large finger joints (see EN 387 [17])

The position of finger joints can be edgewise (fingers visible on the side face; as common in glulam) or flatwise (fingers visible on the narrow face) (see Fig. 4). The advantage of flatwise finger joints is primarily in regard to a higher optical quality as no fingers are visible on the plane surface of CLT. Additional advantages are given in regard to building physics, e.g. airtightness.

The glued finger joint constitutes a quasi-brittle longitudinal joint between board segments which are composed to endless lamellas. In cases where these lamellas are stressed in tension parallel to grain, these stresses have to be primarily transferred by shear within the joint and between the flanks. These shear stresses are optimal for bonded joints in general. Due to the loss in cross section and the specific stress situation, finger joints have to be positioned within the clear wood zone of boards, e.g. in a zone free of knots and apparent local or global grain deviation. In doing so degrees of utilisation of the finger joint even higher than the ones of the board segments (adherends) without joints are possible, although the cross section at the finger tips is reduced up to (12 ÷ 18) % (see Tab. 1). The shear stresses at the flanks occur in interaction with stresses perpendicular to grain. These stresses perpendicular to grain are minimised by reducing the angle α. According to [18], the optimum angle would be $\alpha = 4°$ while a significant reduction in strength can be already observed at $\alpha > 5.7°$. Furthermore, due to stress concentrations at the finger gap a ratio of $l_t / b_t > 1.00$ or at least of > 1.50 is proposed. More details and further discussion as well as a literature survey can be found e.g. in [18], [19], [20], [21], [22] and [5].

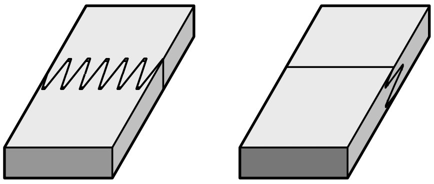


Fig. 4: Edgewise finger joint (left); flatwise finger joint (right)

The production requirements of finger joints are regulated in EN 385 [23] and prEN 15497 [24]. Some technical approvals for CLT also provide regulations in reference to DIN 1052 [25]. The main requirements are: (1) finger joints have to be placed within the clear wood zone of structural timber elements, i.e. free of local (e.g. knots) and global grain deviations and reaction wood; (2) the suitability of the used adhesive system has to be assured (e.g. by technical approvals, EN 301 [26] (type I) or EN 15425 [27]); (3) the technical requirements of using an adhesive system (moisture content, temperature, applied quantity, possibilities of application, bonding pressure, hold time, etc.), as regulated by the relevant standards as well as by the adhesive producer, have to be met. In particular the bonding pressure and the applied quantity of adhesive have to be adjusted to the timber species. Whereas a pressure which is too low may lead to an insufficient wetting of adhesive on all flange surfaces and also to an adhesion which is too low between the adherends during the transport of the lamellas, a too high pressure may provoke unduly splitting of the adherends at the finger base or even of the whole jointed board segments. Thus the longitudinal bonding pressure has to be adapted according to the parameters (i) finger joint profile, (ii) timber species, (iii) moisture content of the adherends, and (iv) cross-section dimension of the adherends. In general it can be said that the same regulations as already given for finger joint connections occur in solid timber and glulam.

To assure an optimum performance of the finger joints, i.e. the suitability of the adhesive system used to produce strong, stiff and durable joints, it is required to adjust the adhesive system to the requirements of the structure and to the timber species. To minimise stress concentrations within finger joints the application of adhesives, which show comparable elastic and shear properties as the adherends, is recommended. In general and as mentioned before only adhesive systems which are permitted to use in load-bearing timber structures, e.g. according EN 301 [26], EN 15425 [27] or according technical approvals, are allowed. Currently mainly melamine-urea-formaldehyde (MUF) and one-component polyurethane adhesives (1K-PUR) are used. Both adhesives have an (nearly) uncoloured bond line, which in case of 1K-PUR is generally more flexible but also more vulnerable against higher temperatures ($T < 60°$), if not modified adequately. Both adhesives are also resistant against exposition to sunlight and humidity and also against hydrolysis. The advantages of MUF can be seen in its higher resistance against high temperatures (e.g. in case of fire) and its gap-filling and penetrating properties. Furthermore, the curing process can be accelerated by increasing the temperature or by means of high-frequency technology. Its disadvantages are the emission of formaldehyde, its limited storage stability (1K-systems) and the strict mixing ratio of resin and hardener (2K-systems). In contrast, 1K-PUR can be easily adapted to the individual production requirements, in particular in regard to its reactivity and curing time. Polyurethanes are also free of formaldehyde and provide some amount of internal pressure during bonding. Due to the increasing formation of gas cavities with increasing bond line thickness, the tolerances in thickness of boards within the same CLT layer have to be strictly kept.

In the course of shifting the focus to strength, it can be said that in general the performance of finger joints stressed in tension parallel to grain primarily depends on the performance of the joined timber elements, the adhesive and the quality of production. Thus the resistance of finger joints is governed by the one of the weakest element. In timber engineering the resistance of adhesive bonding has to be at least as strong as the one of the joined timber elements. Consequently, a single finger joint connection can be reduced to a serial system of $N = 2$ joined timber elements, in the context of strength constraint to the weaker one. Of course, although the quality of joined timber elements is essential, the complexity of production parameters influencing the joint performance individually is subject to each producer and production line (e.g. bonding pressure, adhesive, moisture content, temperature, vibrations immediately after pressing, curing time) making it impossible to model and rule objectively explicit requirements of the finger joint performance. Consequently and in line with current regulations on finger joint tensile strength for glulam according to EN 1194 [28], it is recommended to regulate minimum requirements in relation to the joined timber elements and thus in dependency on the strength class of each CLT layer (e.g. [29]; [5]).

In order to define minimum requirements of the tension strength parallel to grain of finger joints the median strength and, thus, the failure probability of a series of n finger joints and that of a series of $m = (n + 1)$ board segments, which together comprise a lamella at reference length, are kept equally, with $f_{t,0,\mathrm{B},50,m} = f_{t,0,\mathrm{FJ},50,n}$. In congruence with EN 1194 [28], a reference length $l_{\mathrm{L,ref}} = 2{,}000$ mm of the lamella is applied. Examinations conducted on Central European glulam lamellas showed an expectable distance between finger joints of $\mathrm{E}[d_{\mathrm{FJ}}] = [2.0 \div 2.5]$ m ([30]), which is in good agreement with $l_{\mathrm{L,ref}}$. Thus on average and to be on the “safe” side, at least one finger joint per reference lamella ($n \geq 1 = m - 1$) has to be considered. The minimum requirement of the 5 %-quantile of finger joint tension strength $f_{\mathrm{t,0,FJ,05}}$ depending on that of board tension strength $f_{\mathrm{t,0,B,05}}$ at $l_{\mathrm{B,ref}} = l_{\mathrm{L,ref}} = 2{,}000$ mm can be formulated as

$$f_{\mathrm{t,0,FJ,05}} \geq \zeta_{05} \cdot f_{\mathrm{t,0,B,05}}\,. \tag{1}$$

Based on extensive test experiences a coefficient of variation $\mathrm{CV}[f_{\mathrm{t,0,B}}] = (30 \pm 10)$ % for board tension strength parallel to grain can be expected. This range can be further divided into a sub-range of $\mathrm{CV}[f_{\mathrm{t,0,B}}] = (35 \pm 5)$ % in case of visually or mechanically graded boards in only two (three) classes (including the class of reject), and into a sub-range of $\mathrm{CV}[f_{\mathrm{t,0,B}}] = (25 \pm 5)$ % if the boards are mechanically graded in more than two (three) classes (cf. [31]; [29]; [5]). In regard to the tension strength of finger joints a range of CV[$f_{t,0,FJ}$] = (15 ± 5) % is expectable (cf. [29]; [5]). Based on an extensive data analysis and in congruence with EN 385 [23] and prEN 15497 [24] the two-parametric lognormal distribution 2pLND is taken as representative distribution for $f_{t,0,B}$ and $f_{t,0,FJ}$. For reasons of simplicity both properties are modelled as being independent of each other. Thus a very simple model approach can be formulated. Tab. 2 provides the minimum requirements of the finger joint tension strength based on the expected ranges of CV[$f_{t,0,B}$], CV[$f_{t,0,FJ}$] = 15 % and $n \leq 2$ (cf. also [5]). In this way, a very simple approach of high practical relevance is given.

Tab. 2: Minimum requirements of finger joint tension strength parallel to grain

$f_{t,0,FJ,05} \geq \zeta_{05} \cdot f_{t,0,B,05}$	**ζ_{05} = 1.40**	for CV[$f_{t,0,B}$] = (35 ± 5) %
	ζ_{05} = 1.20	for CV[$f_{t,0,B}$] = (25 ± 5) %

Regulations for continuous internal as well as semi-annual external quality assurance can be found in the technical approvals as well as e.g. in prEN 16351 [1], the European standard for CLT. Further details on quality assurance procedures are discussed later in chapter 3.

2.3 Production of single layers (optional)

In general, the producers of CLT aim on reducing the width of gaps. This is achieved in respect to building physic aspects (in particular in regard to fire design, airborne sound and airtightness) but also in regard to joining technique, in particular considering pin-shaped fasteners like nails, screws or dowels. A further reason can be found in aesthetics if the plane surface of CLT is left visible in final use.

As a consequence, some CLT production lines create single-layer panels, which are further cross-wise surface bonded to CLT as an intermediate step. These solid panels are applied to the whole CLT or only to specific layers, e.g. to the top. In doing so, gaps can be completely eliminated or at least reduced to gaps between the panels. A further advantage occurs in final surface pressing to CLT. Since the surface of these panels is already smooth, equalised and of course more precise in thickness than CLT composed of single boards, a lower surface bonding pressure is required. Depending on the thickness of the single-layer panels and the used timber species, both are relevant parameters to the expectable plate stiffness. Thus they are pertinent to the resistance against pressing. A pressure as reachable in vacuum presses or by bracket, nail or screw pressing can be already sufficient for an adequate bond quality. The suitability of each pressing procedure, in particular in connection with the used adhesive system and the allowed tolerances in glue-line thickness, has to be clarified and assured. For further details see section 2.5. A further advantage of single-layer panels is the defined edge bonding between the lamellas in contrast to an incomplete and undefined edge bonding which sporadically occurs during edge and surface pressing of single boards to CLT. In particular in case of large-sized CLT elements edge pressing is usually limited to layers with orientation in direction of production. Therefore, these layers are overlapping of the transverse layers.

As already mentioned, a defined edge bonding has advantages in building physics, e.g. in regard to fire, airborne sound and airtightness. In fact, numerous technical approvals for CLT allow a ratio of w_B / t_B smaller than four, if the boards or laminations are edge bonded. Nevertheless, due to internal stresses caused by swelling and shrinking as consequence of climatic variations the occurrence of checks on the surface of CLT as well as within the CLT layers cannot be avoided. Thus the advantages of edge bonding on building physics and the mechanical potential of CLT can only be charged to a certain limit. As consequence of the quasi-rigid connection between the boards, an irregular pattern of checks can be expected because of the fact that longitudinal checks seldom occur in the bond line. In contrast, in CLT composed of layers of boards without or only undefined edge bonding the swelling and shrinkage takes place between the boards and results in a more regular pattern of gaps (see Fig. 5).

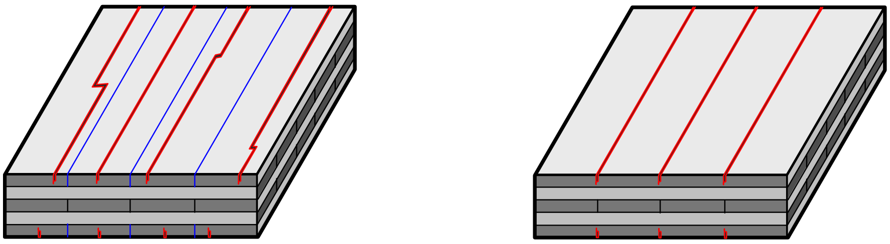


Fig. 5: Checks due to swelling and shrinkage in CLT with edge bonded top layers (left) and without edge bonding (right)

During the production of single-layer panels the suitability of the adhesive system used for edge bonding has to be assured in the frame of an internal and external quality control. Frequently used and suitable adhesive systems are e.g. aminoplast-adhesives, according to EN 301 [26] (type I; melamine-formaldehyde, MF and melamine-urea-formaldehyde, MUF), and one-component polyurethane adhesives (1K-PUR), according to EN 15425 [27]. For more information on adhesives and quality control see chapter 3.

With regard to producing single-layer wood panels as intermediate product in CLT production there can be principally differentiated between three approaches:

2.3.1 Approach 1: single-layer panels gained by edge bonding of boards or lamellas

The used board material has to be adjusted to strength (or stiffness), e.g. according to EN 14081-1 [11] or DIN 4074-1 [12]. Thus the same requirements as given in section 2.1 and 2.2 can be applied. The four-sided planned boards of specific length, with or without finger joints, are continuously joined to endless plates by edge bonding. These single-layer panels are subsequently equalised and formatted according to the dimensions required for longitudinal and transverse layers of CLT. Since these layers are subsequently composed to CLT, there are normally no specific mechanical requirements of the edge bonding. So far the requirement of $w_P \geq 4 \cdot t_B$, with w_P as the width of the panel or the expectable distance between checks due to swelling and shrinkage or distance between relieves, is fulfilled. This limit has been introduced to prevent early failures in rolling shear and has been anchored in numerous technical approvals for CLT.

2.3.2 Approach 2: single-layer panels according to EN 13986 [32]

The requirements according to EN 13986 [32] or of appropriate technical approvals are applied. Subsequently it has to be ensured that the physical / mechanical properties, as required for composing single layers to CLT of a specific strength class, are met. It has to be mentioned that the mechanical properties of single-layer panels according to EN 13986 [32] are based on plate-stripes. The strength grading as mentioned before in section 2.3.1 is not applied. Thus the suitability and quality of the panels for the production of CLT has to be assured by the implementation of an adequate internal and external quality assurance. EN 13986 [32] gives also specific requirements of the shear strength of the edge bonding, which are regulated depending on later service class.

2.3.3 Approach 3: single-layer panels gained by axial splitting of glulam

In this approach single-layer panels are gained by axial splitting of glulam which is normally done by band resaws. In general only homogeneously composed glulam shall be used. The strength grading performed on finger jointed lamellas of the glulam beam (e.g. according to EN 14081-1 [11] or DIN 4074-1 [12]) is of course not transferable to the panels. On the subject of the second approach in section 2.3.2 again an adequate internal and external quality assurance procedure has to be set up to approve the adequacy of the panels for CLT production.

In a further step, independent of the approach and before pressing to CLT the single-layer panels are in general planned or sanded. To guarantee that the whole surface area of CLT is under equal and uniformly distributed pressure smoothness and the prevention of a minor tolerance in average thickness (e.g. according to [33] of ± 0.15 mm) has to be maintained.

2.4 Application of adhesive for surface bonding

In general the guidelines and requirements of the adhesive manufactures have to be followed. It has to be remarked that some parameters, like bonding pressure, quantity of applied adhesive, moisture content of adherends and others are based on experiences made so far with glulam. In the meantime some adhesive producers have adapted their regulations for CLT. In particular the parameters bonding pressure and applied quantity are of relevance (cf. e.g. section 2.5.1). In comparison to GLT the possibility that the applied adhesive is pressed out from the bond lines of the plate-like product CLT is significantly reduced. This aspect requires consideration in regulating the pressing conditions. This is also confirmed in section 2.5.1 referencing [34]. In this work very good and sufficient bond qualities have already been reached by applying the minimum of by adhesive producers proposed quantity of adhesive per square meter.

The application of the adhesive to surface bonding is normally carried out mechanically and without contact (i) on single lamellas in a continuous through-feed device or (ii) on CLT layers already pre-positioned in a positioning or press bed. A line-wise discrete application of adhesive is preferred.

2.5 Composing and pressing of boards or single layers to CLT

2.5.1 Some general comments and recommendations for bonding pressure

In general CLT can be composed of flexible connected boards, lamellas or layers, e.g. by joining them crosswise by means of ring-shank nails (e.g. [35]), hardwood dowels (e.g. [36]) or hardwood screws (e.g. [37]). Of course, more generally CLT is composed of quasi-rigidly connected lamellas or layers, i.e. by surface bonding. This contribution focuses on quasi-rigidly composed CLT elements.

Depending on the pressure device the following differentiation can be made:

1. surface bonding by means of hydraulic press equipment;
2. surface bonding by means of vacuum press equipment;

(3) surface bonding utilising the pressure of screws, brackets or nails.

Depending on the device, bonding pressures of (0.10 ÷ 1.00) N/mm² and even higher can be provided by (1) a hydraulic equipment, whereas vacuum presses (2) and pressing with screws, brackets or nails (3) attain bonding pressures in the range of (0.05 ÷ 0.10) N/mm² and (0.01 ÷ 0.20) N/mm², respectively (cf. e.g. [38]).

Of course regulations of an ideal surface bonding pressure for CLT are still missing. Thus a more general discussion for further clarification is provided. Generally, in cases of suitable surface condition of flatness and of only negligible deviations in thickness of the adherends within and between the single layers for CLT production theoretically no bonding pressure is required. In practice there is always some roughness on the surface, warp and twist of the adherends and deviations in the thickness of the adherends. Consequently, a minimum bonding pressure is required and has to be regulated at best in dependency on the main parameters. The demand on a minimum bonding pressure can be also made due to the adhesive application system. For example, in case of line-wise application a specific minimum pressure securing a complete wetting of the surface is required. Thus the main parameters defining the requirements of a minimum bonding pressure are specified to ensure (i) a complete wetting and (ii) a defined permitted bond line thickness. In regard to (ii) types of adhesive differ first in terms of close contact adhesives and gap-filling adhesives and secondly in means of swelling adhesives (e.g. polyurethane adhesives) and shrinking adhesives (e.g. aminoplast- and phenoplast-adhesives). For ensuring a defined bond line thickness the two parameters applied, quantity and bonding pressure, have to be borne in mind. According to [38] and due to swelling and shrinking, the minimum bonding pressure in case of phenol or melamine based adhesives is in general in the range of (1.40 ÷ 2.00) N/mm² (!), whereas for polyurethanes (0.01 ÷ 0.10) N/mm² should be sufficient. Following the regulations for the production of glulam in EN 386 [39] and prEN 14080 [13] a surface pressure of 0.60 N/mm² for $t_B \leq 35$ mm and (0.80 ÷ 1.00) N/mm² for 35 mm $< t_B \leq 45$ mm thick lamellas without relieves is given. The regulations depending on the lamella thickness take account of the resistance of lamellas against deformation, i.e. against longitudinal and transverse bending deformation and torsion.

Besides the minimum also the maximum allowable bonding pressure requires regulation. It is known that a too high pressure causes damage of the adherends' surfaces ([40]), e.g. by crushing the cell structure. Consequently a reduced adhesive penetration and shear resistance ([41]) can be observed in combination with an increasing possibility of exorbitant squeezing out of adhesive from the bond line, which causes insufficient bonding. Thus the bonding pressure has to be also regulated in dependency of the timber species. This is of vital importance on the one hand due to the expectable resistance against torsional and bending deformations and on the other hand due to the differences in the stress-strain curves in compression perpendicular to grain and hereby in particular in regard to the proportional limit of the linear-elastic course. According to EN 408 [42], on the basis of compression perpendicular to grain tests accomplished on Norway spruce (*Picea abies*) following statistics can be found: $f_{c,90,mean} = (3.0 \div 3.4)$ N/mm², $f_{c,90,05} = (2.2 \div 2.5)$ N/mm² and a coefficient of variation $CV[f_{c,90}] = (22 \div 28)$ % ([43]). The proportional limit can be estimated to be at 30 % of $f_{c,90}$ (according to [44] roughly at 50 %). Thus, to widely (≥ 95 %) prevent plastic deformations on the surfaces of adherends, the upper limit of bonding pressure can be estimated with 1.10 N/mm². In [44] it was found that the cell structure in Norway spruce starts to be damaged already at 0.60 N/mm² and 1.00 N/mm², respectively, in cases of horizontal and vertical annual growth rings, while a decrease in shear strength was already noticed at a pressure of ≥ 0.40 N/mm² and ≥ 1.0 N/mm². Following [45] in Norway spruce the internal pressure has to be limited to ≤ 1.0 N/mm². Thus the externally applied pressure needs to be adapted to the adhesive system, no matter whether it swells or shrinks, and to the swelling pressure of the timber itself as consequence of surface wetting. Of course, as the annual ring pattern for products like glulam or CLT is not restricted in case of Norway spruce or comparable timber species, the surface bonding pressure has to be limited to $\leq (0.4 \div 0.6)$ N/mm².

To summarise in brief, the required surface bonding pressure can be defined as function of (i) the adhesive system, (ii) the timber species, (iii) the geometry of the adherends in regard to roughness and flatness of the surface and allowed tolerances in thickness, (iv) the adhesive application system, and (v) the applied quantity of adhesive. The applied quantity itself depends on the roughness of the adherend's surface and consequently on the timber species (for example: ringporous vs. diffuse porous hardwoods).

For clarifying the consequences of the interacting parameters bonding pressure and applied quantity on the CLT production a comprehensive research project was conducted (cf. [34]). In the context of this project two types of 1K-PUR adhesives, three bonding pressures of (0.1, 0.3, 0.6) N/mm² and various applied quantities, which were defined to secure a complete wetting in unidirectional surface bonding in dependency of bonding pressure, were investigated. Additionally, the effect of cyclic climatic variations (20 °C / 90 % rel. humidity and 30 °C / 40 % rel. humidity; quantities of cycles: 0, 10, 21, 25) on the properties of bonding was also analysed. This research was performed on under specific conditions in laboratory produced three-layered CLT elements of Norway spruce of strength class C16 and C24 according to EN 338 [8]. The surface bonding properties were investigated by means of rolling shear tests on whole CLT elements in bending according to EN 408 [42], block (rolling) shear tests on the single glue line according to EN 392 [46] and delamination tests according to EN 391 [47], approach B. To summarise, although the applied adhesive quantities were generally on the lower limit of producer's recommendations, the investigated bonding pressures were found to be sufficient to realise adequate bond qualities. So far the dispersion in thickness between boards of the same CLT layer was kept low. The relevance of this demand can be easily demonstrated by a simple calculation example: With Hook's law for linear elastic material and with the parameters for C18 according to EN 338 [8] with $E_{\text{c,90,mean}} = 380$ N/mm² it can be shown that with regard to compression a 40 mm thick board by 0.10 mm an average surface pressure of 0.95 N/mm² is already required. In contrast to this, parameters like warp or twist of the board material showed nearly no or at least negligible effects on surface bonding. This is because of the relatively low E-modules longitudinal and transverse in bending and the G-module of timber in torsion. Of course, a positive relationship between bonding pressure and shear strength was observed in cases where the applied adhesive quantity was beneath the recommended quantity and thus was too low or the deviations in thickness were too high.

Hence, it can be stated that also for CLT composed of single boards a low pressure can be sufficient, as far as a very strict and small tolerance in the thickness of lamellas within one CLT layer is ensured. Therefore the parameter board thickness should be controlled in frame of the internal quality assurance procedures. Following the calculation example mentioned before and in regard to the thickness range of CLT lamellas, it is highly advisable to make use of a tolerance of $\leq (\pm 0.10)$ mm, although this demand is stricter than that meanwhile partly anchored in technical approvals for CLT (cf. e.g. [33], [48], [49]). This strict tolerance is also argued concerning the requirements of the allowed bond line thickness of e.g. (0.1 ÷ 0.3) mm in case of 1K-PUR.

2.5.2 CLT production by means of hydraulic press equipment

By means of hydraulic press equipment it is possible to provide nearly every desired surface pressure. Of course current systems provide an upper limit of 0.8 (1.5) N/mm², which makes them flexible enough to extend the productions also to thicker and thus stiffer single-layer elements and also to hardwoods. In contrast to vacuum facilities or nail, bracket or screw pressing, it is possible to provide specific edge pressure, e.g. solely on the top, transverse or on individual layers for assuring homogeneously closed gaps. Of course hydraulic press systems are normally restricted to produce even CLT elements without curvature or of other shapes. As a consequence of parallel pressing surfaces, it is also not possible to balance local unevenness or deviations in thickness as it is for example provided in a vacuum press.

Fig. 6: Placing and aligning of the single layers (left); positioning of layers and application of adhesive (right) (© Minda-Industrieanlagen GmbH / DE)

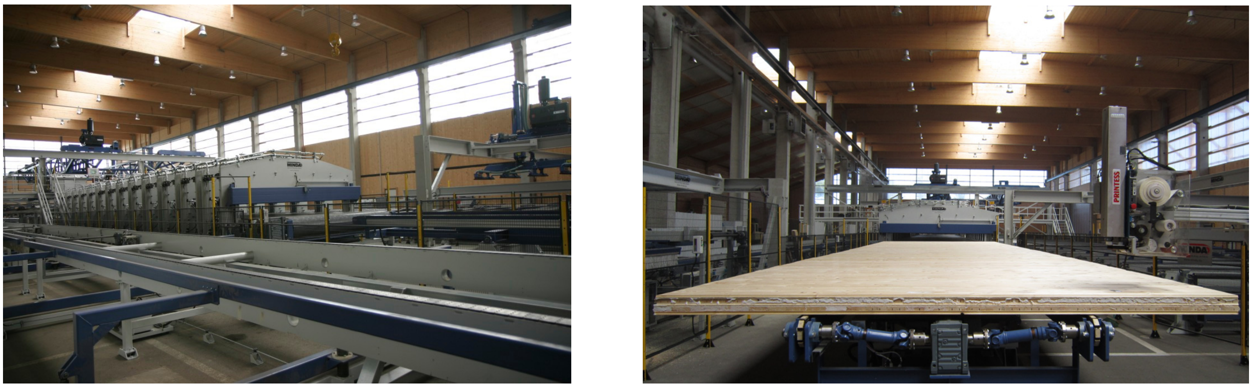


Fig. 7: Hydraulic surface and edge pressing device (left); unloading of ready produced CLT (right) (© Minda-Industrieanlagen GmbH / DE)

A great advantage of hydraulic facilities is their flexibility in regard to automation of process steps before, during and after pressing. This comprises the positioning and alignment of single boards or layers, the application of adhesive, the conveying into and out of the press, the application of specific edge pressure and the pressing itself, in which differentiation has to be made also in regard to the adhesive system and the curing process (cold, hot or with high frequency). Depending on the production volume and market orientation modular processing units with different degrees in automation are provided by some press producers. For example Minda-Industrieanlagen GmbH / DE offers a press system (cf. Fig. 6 and Fig. 7) with stages of expansion semi-mechanically equipped with three press cycles per shift up to twelve press cycles per shift in a fully mechanical processing. Consequently, it is possible to move step-by-step into the CLT market.

Depending on the CLT production, further differentiation can be made in press facilities for small CLT elements, which are further connected by large finger joints, and large-sized CLT elements with a dimension of up to l / w / t = ≤ 18.0 m / ≤ 3.5 m / ≤ 400 mm. In dependency on the required production volume and the adhesive properties, single or multiple CLT elements can be produced in one press cycle. Also based on the production volume and the degree of automation, it may be meaningful to adapt the adhesive system to allow for example one press cycle every 40 minutes.

Further differentiation can be made in the production of CLT elements with or without edge bonding and with or without door and window openings. In the last case the adhesive application system has to be adapted to omit these openings. In regard to the press system itself further differentiation is possible in (i) fixed press facilities and moving CLT elements (e.g. Minda-Industrieanlagen GmbH / DE, Springer Maschinenfabrik AG / AT, Kallfass GmbH / DE) and in (ii) horizontally displaceable press facilities as e.g. constructed by Fr. Leiße & Söhne GmbH & Co. KG / DE. The productivity of current press systems allows a CLT production volume of 25,000 m³ per year and shift.

A comparable press facility is provided by Ledinek Engineering d.o.o. / SI. Here a pneumatic press system is combined with tie bars.

2.5.3 CLT production by means of vacuum press equipment

Another possibility to produce CLT as rigid composite provided by adhesive bonding is to press single boards or layers by vacuum (cf. Fig. 8). In doing so a pressure of (0.05 ÷ 0.10) N/mm² can be reached. Thus specific and strict requirements of the surface quality, in particular on evenness and minor tolerances in thickness, have to be met to assure an adequate bond line quality.

Also limits in warp and twist have to be considered. On the subject of reducing the stiffness against bending and torsion deformations, relieves are made longitudinal to the grain and, according to prEN 16351 [1], not deeper than 90 % of the lamella thickness and not wider than 4 mm in width. Due to the fact that, as already mentioned, also in this case the compliance of the ratio d_R / $t_B \geq 4$ has to be kept or reduced, rolling shear strength of CLT needs to be considered. Because of the limited bonding pressure also a limitation in processable layer thickness or timber species can occur. In regard to the requirements of adherends' surface, evenness and thickness tolerances usage of single-layer panels can be advantageous.

Fig. 8: Vacuum press in combination with an adhesive application system (© woodtec Fankhauser GmbH / CH)

Overall vacuum press facilities allow an economical surface bonding and are well suited for small and median CLT productions with a production capacity of (2,000 ÷ 5,000) m^3 per year and shift. The processing itself is in general semi-mechanical. The boards or layers are placed manually whereas adhesive application is operated semi-mechanical. It is also possible to compress the top layers by means of lateral pressing bars before the air in the airtight synthetic rubber foil is evacuated and the CLT is compressed homogeneously. This homogeneously distributed pressure in principle enables to produce also curved or general shaped CLT elements and offers also the production of composite elements like box-beams or rib floors. Also local thickness deviations can be balanced to some amount and sufficient bond qualities achieved.

2.5.4 CLT production by means of bracket, nail or screw pressing

Another alternative approach for producing CLT as rigid composite is to provide the bonding pressure discretely by nails, screws or brackets. The herein commonly achieved pressure amounts to (0.01 ÷ 0.20) N/mm^2 and thus is comparable with vacuum press facilities. Consequently, the same requirements of the base material used for composing CLT can be applied, cf. section 2.5.3. The advantage of this approach is given by the minimum efforts and investments necessary to produce CLT. Of course, in comparison to a flexible composed CLT, e.g. in which the layers are solely connected by nails, screws or brackets, knowledge and experience about adhesive bonding is required to assure a proper production.

To prevent damage of tools which are used later in cutting and joining processes it is advisable to use aluminium instead of steel fasteners. Following e.g. [50] aluminium brackets can be found as being appropriate. To achieve a sufficient and widely homogeneously distributed bonding pressure it is required to regulate the spacings between the discretely placed fasteners. Therefore the rules for screw pressings in DIN 1052 [25] can be used as basis. According to this standard, only self-tapping full-threaded wood screws with a nominal diameter $d \geq 4$ mm are allowed. The maximum area allocable per screw is $A \leq 15{,}000$ mm^2 and the maximum spacing amounts to 150 mm. The thickness of structural timber used for each layer is restricted to $t \leq 35$ mm, whereas the use of engineered timber products according to DIN 1052 [25], section 14.1 (4) up to $t \leq 50$ mm is allowed.

2.6 Large finger joints between CLT elements

An alternative production process of CLT involves producing small CLT elements in single or multi-layer cycle presses first and afterwards joining them to larger CLT elements by means of large finger joints. However, it is also possible to use large finger joints as connections in order to join already large-sized CLT elements or cut-outs from door or window openings. These large finger joints comprise the whole cross section of joined elements. The advantage of producing small elements, e.g. as done in [48], is given by the small-scaled press and the much smaller forces as well as in the handling of the elements before and after pressing. A common and standardised profile for large finger joints is defined with $l_{FJ} = 50$ mm, as presented in Tab. 1. The production requirements are based on the experiences gained with glulam and are given in reference to EN 387 [17] and section 3.5. As consequence of the joint, the bending strength of CLT elements at that position has to be reduced on the basis of a 25 % reduction of the characteristic 5 %-quantile bending strength of the base material (see e.g. [48]). Of course, in case of adequate planning processes this does not or only negligibly restrict the design process.

2.7 Finish of standard CLT elements

After pressing, standard CLT elements are trimmed on their edges. The surface of the elements after pressing is treated differently, without further processing by planning or sanding. Depending on later use, also the application of additional non load-bearing layers like OSB, acoustic panels, gypsum plaster boards or three-layered solid wood panels is possible (cf. also section 2.1). These additional layers are primarily connected by surface bonding.

2.8 Cutting and joining: customising

Cutting and joining of CLT elements immediately after production and finishing constitute essential and logical process steps in an order-related, small (single) batch production. It is the aim to continue the precision achieved in production also in cutting and joining. Approved devices are portal machines which operate as multiple processing centres (e.g. of Hans Hundegger Maschinenbau GmbH / DE). After the CLT element has been aligned accurately, these machines accomplish all relevant processes for dimensioning and further joining, like trimming, cutting, milling (e.g. for connection technique, stepped rabbet or profiling of edges for later joining of e.g. ceiling elements, for installation channels, etc.), drilling (on both surfaces and all edges up to 2 m in depth from one side) on both surfaces (top and bottom) and all four edges (cf. Fig. 9), including marking and labelling. The tools (moulding cutters, saws, chain saws, etc.) provided in tool magazines are available on time. Thus large-sized CLT elements in thickness up to 350 mm, in length up to 16 m and in width up to 4.3 m can be readily processed to wall, floor and ceiling elements. Another advantage of these processing centres is the possibility to encase the device for minimising emissions of noise, dust and chips whereby dust and chips as by-products can be collected in concentrated form.

Depending on the CLT production volume and on the market orientation, for securing a continuously running production it can be meaningful to operate more than one processing centres parallel. Therefore process centres in various dimensions and configurations are available and systems are provided, which allow step-by-step adaptation on production volume and market demands. In dependency on the required flexibility, three- to five-axis machining centres are available. Of course not only the processing centres, but also the combination with software packages for optimising the layout and thus the degree of utilisation of CLT elements together with a well-operating process planning office create an economical and powerful customising centre and add value to the product CLT. Meanwhile also customising centres without own CLT production have been established in combination or cooperation with carpentries or assemblers.

Fig. 9: Machining centre: moulder (left), chain saw (middle), saw (right) (© Hans Hundegger Maschinenbau GmbH / DE)

In regard to the assembling on site it is essential to optimise the logistics and to load of the elements after cutting and joining e.g. on trucks in inverse order to that required later on site.

3. Factory production control (FPC) – internal quality assurance

The aim of this chapter is to present the main internal test and monitoring procedures as required and regulated within technical approvals for CLT as well as within prEN 16351 [1] as far as the factory production control (FPC) is concerned. The following sections individually give (minimum) requirements for each quality criteria whereby the requirements of prEN 16351 [1] are treated first. Consequently, additional processes for quality assurance and monitoring as partly given in technical approvals of Germany and the European Technical Approvals are briefly presented.

Complementary to FPC an external quality control by an independent accredited institution is generally required semi-annually. Thereby the conformity of production and monitoring processes according to the underlying guidelines, approvals and standards is assessed. These institutions are also responsible for initial type testing and the determination of some process parameters (e.g. declared strength values for (large) finger joints, etc.). These external test and evaluation procedures are not part of this chapter.

Within the frame of FPC it is also required to establish an internal guidance procedure for quality control. This procedure should provide regulations and responsibilities for testing and monitoring of production processes and in particular of actions in cases in which test results are conspicuous or do not meet the requirements.

3.1 Control of climatic conditions during production

To ensure an orderly bonding the requirements given by the adhesive manufacturer, i.e. in regard to temperature of adherends and surrounding, the relative humidity and moisture content of the adherends, the applied adhesive quantity, the time schedule, the bond pressure, etc. have to be met. The prEN 16351 [1] recommends some of these parameters as general minimum conditions for the production of CLT, e.g.

- during bonding: $T \geq 15$°C and rel. humidity (40 ÷ 75) %;
- during curing: $T \geq 18$°C and rel. humidity ≥ 30 %;
- moisture content of adherends u = (6 ÷ 15) % (≤ 18 % in case of preservative treatment);
- maximum difference in moisture content between two parallel layers $\Delta u \leq 5$ %.

3.2 Delivery control of adhesives

According to prEN 16351 [1] it is required to control every dispatch of adhesive in regard to quality and suitability for the production of CLT or for a specific process step (e.g. finger joints, edge and surface bonding). Additionally, the adhesive system used for large finger joints has to be controlled in every shift it applies. The adhesive systems which are principally allowed for use in CLT production according to prEN 16351 [1] are:

- phenoplast- and aminoplast-adhesives according to EN 301 [26], type I or according to technical approvals which certify the appropriateness of the adhesive system for load bearing timber structures and in particular for CLT for use in service class one or two; these adhesives (primary MUF) are principally applied to bonding of (large) finger joints as well as to edge and surface bonding; if used for (large) finger joints the minimum holding time for longitudinal pressure and the mixing ratio of synthetic resin and hardening agent have to be monitored in addition; for large finger joints the applicability is additionally limited to adhesive systems which are certified for bond line thicknesses up to 1 mm;

- one-component polyurethane adhesives (1K-PUR) according to EN 15425 [27] or according to technical approvals which certify the appropriateness of the adhesive system for load bearing timber structures and in particular for CLT for use in service class one or two; this type of adhesive is in principal suitable for bonding of (large) finger joints as well as edge and surface bonding;
- emulsion-polymer-isocyanate adhesive (EPI) as far as the requirements are met as given in EN 15425 [27] or within a technical approval which certifies the appropriateness of the adhesive system for load bearing timber structures and in particular for CLT in service class one or two; this type of adhesive is in principle allowed for bonding of finger joints as well as for edge and surface bonding, but according to prEN 16351 [1] not for large finger joints.

3.3 Delivery control of the base material used for load-bearing purposes (solid timber / single-layer wood panels)

According to prEN 16351 [1], CLT can be produced of structural timber adjusted according to EN 14081-1 [11] and / or of engineered timber products (e.g. single-layer panels) which met the requirements of EN 13986 [32] or EN 14374 [51]. For structural timber so far only softwood species are considered. In regard to the single layers it is allowed that ≥ 90 % of the board material is of the declared strength class, e.g. according to EN 338 [8], whereas up to ≤ 10 % of the boards can be of a strength class with a maximum deviation from the declared strength values of 35 %.

3.4 Minimum FPC requirements of finger joints

The requirements concerning the production of finger joints in prEN 16351 [1] follow in principle the ones of EN 385 [23] or prEN 15497 [24]. In the context of FPC the fulfilment of minimum requirements of finger joint strength can be tested in tension parallel to grain or bending. Following prEN 16351 [1], similar regulations to the glulam product standard EN 1194 [28] can be found, for example

$$f_{\mathrm{t,0,FJ,k}} \geq 5 + f_{\mathrm{t,0,B,k}}\,; \tag{2}$$

$$f_{\mathrm{m,FJ,k}} \geq 8 + 1.4 \cdot f_{\mathrm{t,0,B,k}}\,. \tag{3}$$

Testing comprises at least three specimens per shift and production line of the highest produced strength class or strength profile and per adhesive. The test can be performed flatwise in four-point bending or in tension parallel to grain, both in reference to EN 408 [42]. Deviating from this standard the maximum (failure) load has to be reached within (60 ± 15) s. Furthermore, in case of bending tests the test span can be reduced to $l_{\mathrm{span}} \geq 15 \cdot t_{\mathrm{L}}$ and in tension to a free test length of $l_{\mathrm{free}} \geq 3 \cdot w_{\mathrm{L}}$, respectively, with t_{L} and w_{L} as thickness and width of the laminations. It has to be ensured that at least five of the last 100 test values are below the declared characteristic 5 %-quantile of the finger joint strength $f_{\mathrm{FJ,dc,k}}$ and that within the last 15 tests none of the tests was below $f_{\mathrm{FJ,15}}$, with $f_{\mathrm{FJ,15}} = k_{15} \cdot f_{\mathrm{FJ,dc,k}}$ and k_{15} as parameter which considers the dispersion in strength (restricted to CV[f_{FJ}] ≥ 10 %) and the sample size assuming a lognormal distributed strength.

Following the German technical approvals for CLT, in general testing of at least two specimens per shift is required. FPC in regard to finger joint strength can be also done by bending and tension tests, the last one with a minimum test length of $l_{\mathrm{free}} \geq 200$ mm. The requirements of the bending strength $f_{\mathrm{m,FJ,k}}$ are regulated in reference to DIN 1052 [25], annex H, Table H.1 or DIN 68140-1 [52] (cf. Tab. 3).

Tab. 3: Minimum requirements of $f_{\mathrm{m,FJ,k}}$

strength class acc. to EN 338 [8]	**$f_{\mathrm{m,FJ,k}}$ [N/mm²] acc. to DIN 1052 [25]**	**grading class acc. to DIN 4074-1 [12]**	**$f_{\mathrm{m,FJ,k}}$ [N/mm²] acc. to DIN 68140-1 [52]**
C16	≥ 25	**S7 / MS7**	-
C24	≥ 30	**S10 / MS10**	≥ 30
C30	≥ 35	**S13**	≥ 35
C35	≥ 40	**MS13**	≥ 40
C40	≥ 45	**MS17**	≥ 45

For example in [53], the minimum requirement of tension strength is regulated by 70 % of $f_{\mathrm{m,FJ,k}}$, according to DIN 1052 [25]:

$$f_{\mathrm{t,0,FJ,k}} \geq 0.7 \cdot f_{\mathrm{m,FJ,k}}\,. \tag{4}$$

Of course, in regard to the arguments in section 2.2 it is recommended to regulate the minimum requirements of the finger joint strength based on tension tests parallel to grain according to the formulations in section 2.2, Tab. 2 and, thus, in dependency on the stochastics of the material.

3.5 Minimum FPC requirements of large finger joints

According FPC in prEN 16351 [1], the production requirements of bond line thickness and tip gap of the finger joint have to be controlled concerning at least one specimen per shift. The maximum allowed bond line thickness is 0.5 mm for phenoplast- and aminoplast-adhesives and 0.3 mm for 1K-PUR. The relative tip gap has to be within $e = (0.02 \div 0.10)$, with $e = l_{\mathrm{t}} / l_{\mathrm{FJ}}$. The characteristic 5 %-quantile of the bending strength of large finger joints $f_{\mathrm{m,LFJ,k}}$, determined by means of four-point bending tests by large finger joints connected full-size CLT-elements according to EN 408 [42], has to be at least as high as the declared value $f_{\mathrm{m,LFJ,dc,k}}$.

FPC requirements concerning large finger joints in German technical approvals for CLT are frequently referred to EN 387 [17]. Again this standard imposes requirements of the geometry, the bond line thickness (in general ≤ 0.5 mm) and the gap tip $l_{\mathrm{t}} = (1 \div 6)$ mm. The compliance has to be controlled concerning at least one cylindrical specimen (diameter 25 mm) per shift or at least regarding one per ten produced joints taken from the centre of the joint. If all test results within a period of at least three months fulfil the requirements, the sampling may be reduced to one per 30 produced joints, but at least one per shift. The bending strength of large finger joints has to be determined on full-size jointed CLT elements according to EN 408 [42] and EN 386 [39]. For example in [48] the minimum required strength is defined as share of the bending strength of the board material, for example

$$f_{\mathrm{m,LFJ,k}} \geq 0.75 \cdot f_{\mathrm{m,B,k}}\,. \tag{5}$$

3.6 Minimum FPC requirements of edge bonding

According to prEN 16351 [1], the resistance of edge bonding has to be controlled by means of block shear tests. Per shift at least one specimen comprising the whole width of a single-layer panel has to be taken and at least two bond-lines need to be tested according to EN 392 [46]. Before testing the compliance of the bond line, the thickness with allowed values has to be checked. The minimum requirements of shear strength are regulated in relation to the share of fibre and wood on the fractured surface, see Tab. 4.

Tab. 4: Requirements of edge bonds according to prEN 16351 [1]

	average value			**single value**		
f_v [N/mm²]	6.0	8.0	≥ 11.0	4.0 ÷ 6.0	6.0	≥ 10.0
FF [%] 1)	≥ 90 %	≥ 72 %	≥ 45 %	100 %	≥ 74 %	≥ 20 %
1) share of fractured surface covered by fibres (share of wood failure)						

The shear strength f_v has to be calculated as

$$f_v = k \cdot \frac{F_u}{A}, \text{ with } A = b \cdot t \text{ and } k = 0.78 + 0.0044 \cdot t, \tag{6}$$

with F_u as the ultimate failure load, A as shear area and k as thickness correction factor.

3.7 Minimum FPC requirements of surface bonding

3.7.1 Delamination according to prEN 16351 [1]

For controlling the adhesion or the resistance against fractures in the bond line, specimens of defined geometry have to be exposed to a specific series of climatic conditions and afterwards the delamination of their bond lines has to be determined. Therefore at least one specimen per 20 m³ produced CLT (or in case of positive results over a time period of at least three month at least one per 40 m³) comprising the whole depth of CLT, in width ≥ (75 ± 5) mm and in length large enough for a surface of A ≥ 10,000 mm² or a cylindrical specimen with a diameter of ≥ (95 ± 5) mm has to be taken. After determining mass and measurement of the length of all bond lines visible on the end-grains the specimen has to be exposed to the following conditions:

- completely submerged and surrounded by water of $T = (10 \div 20)$ °C;
    - exposition to a vacuum of (70 ÷ 85) kPa (absolute pressure (15 ÷ 30) kPa) for 30 min;
    - exposition to a pressure of (500 ÷ 600) kPa (absolute pressure (600 ÷ 700) kPa) for 120 min;
- drying in a chamber at $T = (65 \div 75)$ °C, (8 ÷ 10)% rel. humidity and air velocity of (2 ÷ 3) m/s till (100 ÷ 110)% of the mass before testing is reached; this should be possible within (10 ÷ 15) h;

Afterwards the share of delamination has to be determined on all bond lines. The maximum share of delamination per single bond line and per specimen has to be calculated as

$$\mathrm{Delam}_{\max} = 100 \cdot \frac{l_{\text{max,delam}}}{l_{\text{glue line}}} \ [\%], \tag{7}$$

and the overall share per each specimen is determined as

$$\mathrm{Delam}_{\text{tot}} = 100 \cdot \frac{l_{\text{tot,delam}}}{l_{\text{tot,glue line}}} \ [\%]. \tag{8}$$

The allowed shares of delamination are $\mathrm{Delam}_{\max} \leq 40$ % and $\mathrm{Delam}_{\text{tot}} \leq 10$ %. In case that one or both criteria are exceeded, each bond surface has to be split and the share on surface fractured in wood or covered by fibres has to be determined. Per each bond surface a minimum share of wood and fibre failure of 50 %, and on average of all bond surfaces per specimen a minimum share of 70 % (maximum average delamination of 30 %) have to be kept otherwise the test has failed.

3.7.2 Delamination according to DIN 53255 [54] / DIN 68705-4 [55] and alternative test methods

FPC requirements of delamination in German technical approvals for CLT are in general referred to DIN 53255 [54]. Therein a method for testing the quality and resistance of surface bonding in cross laminated wood and timber products is provided. It examines the local dissociation of each individual bond line by means of a special designed dissociation tool. As stated in prEN 16351 [1], a minimum average share of wood and fibre failure on all bond surfaces per specimen of 70 % is required. Before testing, each specimen has to be exposed to a cycle of specific climatic conditions according to DIN 68705-4 [55], specification for BST 100. In doing so it is differed between a cold water test (24 h completely submerged at $T = (20 \pm 2)$ °C) and a hot water test (4 h completely submerged in boiling water, followed by $(16 \div 20)$ h storage in a climate chamber at $T = (60 \pm 2)$ °C, 4 h completely submerged in boiling water and $(2 \div 3)$ h cooling down completely submerged in water at $T = (20 \pm 5)$ °C).

Alternatively, some approvals allow block shear tests according to DIN 52187 [56] on at least 10 specimens per working day. The average shear strength of the last ten tests shall met $f_{\text{v,mean}} \geq 1.5$ N/mm² and the characteristic 5 %-quantile of the last 100 tests $f_{\text{v,k}} \geq 1.25$ N/mm², but shall not value below 1.00 N/mm².

A further alternative is to perform shear tests according to EN 789 [57], annex C on at least one specimen per working day and thickness range of produced CLT.

Some approvals also allow delamination tests according to EN 391 [47], approach B instead of the delamination test according to DIN 53255 [54]. The climatic conditions as well as the limits are equal to prEN 16351 [1] (cf. section 3.7.1). Tests which exceed the limit $\mathrm{Delam}_{\text{tot}} \leq 10$ % have to be exposed to a second cycle of equal climatic conditions and to a new limit of $\mathrm{Delam}_{\text{tot}} \leq 15$ %. If this limit is also exceeded, the specimen has to be tested according to DIN 53255 [54]. The required minimum average share of wood and fibre failure on all bond surfaces per specimen is 70 %.

3.7.3 Excursus: experiences made with delamination

In reference to section 2.5.1 and to the research project reported in [34], some results and experiences made in regard to delamination are presented. Fig. 10 gives an overview of the results gained by testing CLT specimens in rolling shear according to EN 408 [42] ($l_{span} = 12 \cdot t$) and in delamination according to EN 391 [47], approach B. The results of delamination comprise the maximum delamination per bond line ($Delam_{max}$) and the maximum delaminated bond surface per specimen $A_{delam,max}$. The presented results embrace nine sub-series per each test: three variations in surface pressure (SP; (0.1, 0.3, 0.6) N/mm²) and three variations in number of climatic cycles (CC; 0, 10, 25) to which the specimens were exposed before testing; The climate varied weekly between 20 °C / 90 % rel. humidity and 30 °C / 40 % rel. humidity. Hence, one climate cycle took two weeks and caused a variation in moisture content of (12 ÷ 17) %. Per each sub-series at least five specimens were tested concerning rolling shear and then regarding delamination.

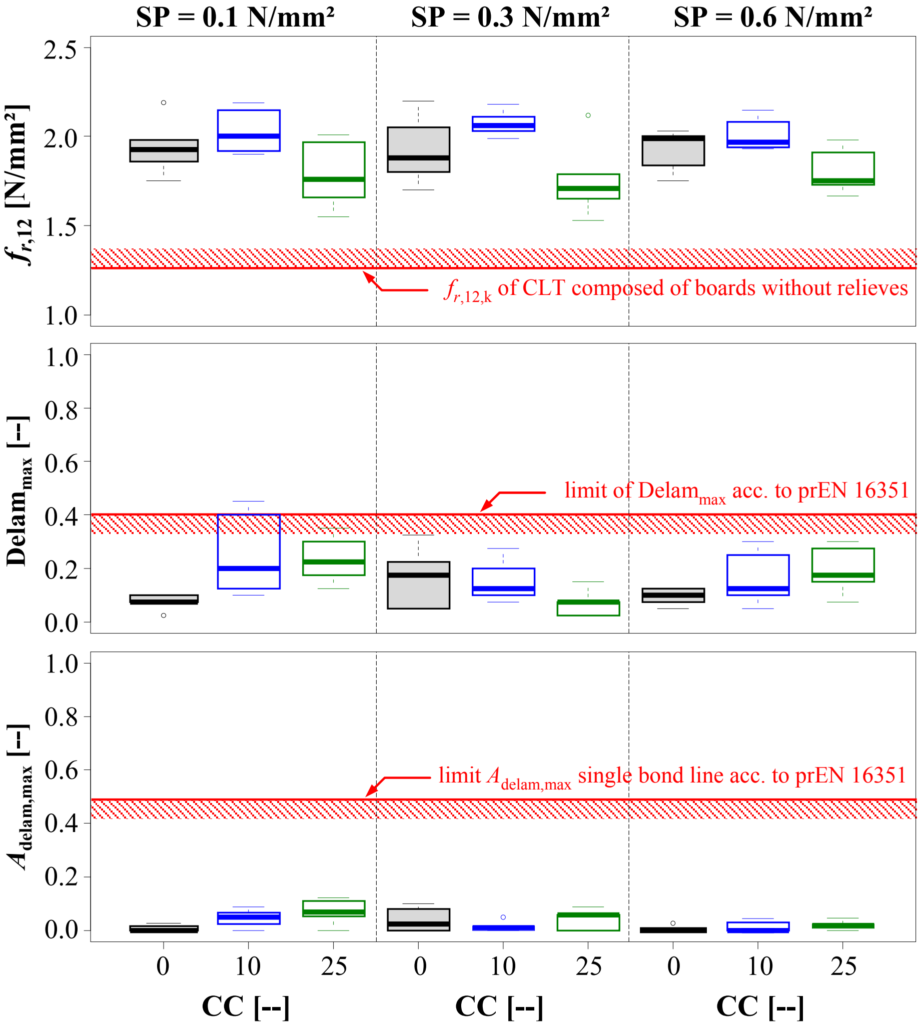


Fig. 10: Results (excerpt) of CLT tested in rolling shear ($f_{r,12}$; above) and delamination ($Delam_{max}$; middle and $A_{delam,max}$; below) in dependency on surface pressure (SP) and number of climatic cycles (CC) together with FPC limits according to prEN 16351 [1] ([34])

To summarise the results briefly it can be said that all specimens tested in rolling shear delivered strength results on the save side. The limits according to prEN 16351 [1] for the two criteria examined in regard to delamination, $Delam_{max}$ and $A_{delam,max}$, were also met except of one sub-series where the limit of $Delam_{max}$ was exceeded. Of course also these specimens passed the test afterwards in examining $A_{delam,max}$. Although a slight increase of CC = 0 to CC = 10 and a reduction in $f_{r,12}$ at CC = 25 can be observed, no relation was found neither between CC and $\text{Delam}_{\text{max}}$, nor between CC and $A_{\text{delam,max}}$ in delamination. In some sub-series a coherent course of $\text{Delam}_{\text{max}}$ and $A_{\text{delam,max}}$ is given. A relation between $f_{r,12}$ and properties of delamination cannot be confirmed. Focusing on delamination the dispersion in $A_{\text{delam,max}}$ is much smaller than in $\text{Delam}_{\text{max}}$. This indicates a higher stability in the results of $A_{\text{delam,max}}$. Although it is not possible on the basis of these tests to relate the delamination results to realistic expositions of structures and to define limits for $\text{Delam}_{\text{max}}$ and $A_{\text{delam,max}}$, experiences gained during testing suggest that the bond line quality is indicated by the combined judgement of delaminated bond lines and identified bond surfaces.

3.7.4 Delamination: conclusions

To summarise, the approach presented in section 3.7.1 examining the delamination of surface bonding in combination with splitting of the surfaces by a metal wedge is preferred. The main reason for this is because it is believed to provide a higher degree in comparability and reproducibility than the alternative methods in section 3.7.2. Of course a fundamental and quantifiable relation between the exposition to extreme climatic test conditions and the practical relevance, in particular with respect to the established service class system, has not been available yet. As it is the case for glulam the limits in delamination for CLT are based on empirical analyses developed and manifested by experiences made so far. Due to the cross laminated structure of CLT and the higher internal stresses in the context of swelling and shrinkage it was necessary to adapt the limits which had been until than anchored for glulam.

3.8 FPC requirements of rolling shear strength of CLT

Following the FPC regulations in German technical approvals for CLT the testing of one specimen per working day in rolling shear by means of a four-point bending test according to EN 408 [42], but with reduced span of $l_{\text{span}} \geq 15 \cdot t$ is required.

3.9 FPC requirements of maximum bond-line thickness according to prEN 16351 [1]

Following prEN 16351 [1] the maximum allowed bond line thickness for aminoplast- and phenoplast-adhesives is $t_a \leq 0.6$ mm and $t_a \leq 0.3$ mm, respectively, for common and separate application of resin and hardener. In case of 1K-PUR the limit is $t_a \leq 0.3$ mm.

3.10 Additional FPC requirements

“Additional requirements” according FPC comprise regulations of (i) the used timber species, (ii) the durability of the base material(s), (iii) criteria for preservative treated base material(s), (iv) criteria for classifying the resistance of CLT if exposed to fire, (v) the dimensions, geometry and assembly, and (vi) the compliance with release limits on formaldehyde and other harmful agents. Further information can be found in the technical approvals as well as in prEN 16351 [1].

4. Main geometrical and technological parameters of CLT

Within this chapter the main geometrical parameters relevant for production of CLT are presented. An overview of the regulation of these parameters according to current technical approvals for CLT in Europe is provided in Tab. 5. To summarise, producers aim on reducing the regular gap width between boards or single-layer panels within one CLT layer. Following the regulations gaps of ≤ 2 mm and ≤ 4 mm between boards in top and core layers, respectively, are common presently. The approvals are widely restricted to softwoods, whereby Norway spruce (*Picea abies*) is definitely preferred. The strength classes of the basic material are dominated by C16 and C24 according to EN 338 [8]. In this regard the quality of the basic material within each CLT layer is judged under relaxed regulations. Common dimensions of CLT are up to 18 m (or even 30 m) in length, up to 4 (4.8) m in width and seldom above (300 ÷ 400) mm in thickness. Although hydraulic press facilities dominate the production of CLT, in volume no tendency can be observed concerning the production parameters "single-layer panels" and "edge bonding". Also the requirements of FPC can be said to be diverse.

The rates of swelling and shrinkage of CLT of Norway spruce (*Picea abies*) in and out of plane as well as differential swelling and shrinkage rates that apply so far to the moisture content of CLT kept within (6 ÷ 22) % are:

- for both directions in plane: 0.02 % per each percent change in moisture content;
- for the direction out of plane: 0.24 % per each percent change in moisture content.

Tab. 5: Overview of some geometrical and technical characteristics of European CLT producers

technical approval	**dimension CLT *l* [m] / *w* [m] / *t* [mm] further information**	**dimension BM (SP) 1) *w* [mm] / *t* [mm] further information**	**timber species 2) strength class**	**max gap width [mm]**	**single-layer panels (Y/N/possible)**	**edge bonding (Y/N/possible)**	**adhesive system 3)**	**surface pressing**	**FPC test procedures for CLT 4)**
[50]	≤18/≤4/60÷400 ≥3 layers	250÷1200/15÷45	SW ≥C16	2(4)	Y	N	EN301 1K-PUR	bonding pressure by brackets	RS; BS; FJ
[58]	≤30/≤4.8/≤300 ≥3 layers	80÷220/10÷33 TL *w*/*t*≥4	SW ≥C16	6	N	-	EN301	-	RS; FJ; DL (D)
[59]	≤30/≤4.8/30÷300 ≥3 layers	80÷220/10÷33 TL *w*/*t*≥4	SW ≥C16	6	N	N	EN301 EN15425	-	-
[60] 5)	-/-/19÷42 3 layers	T*l* 60÷150/5.75 C*l* 19÷150/7.5÷30.5	SW	-	Y	-	-	-	D; B(t)
[61] 5)	-/-/16÷57 3 layers	T*l* 80÷140/5.5÷13.2 C*l* 80÷140/5÷31.6	SW ≥C16	-	Y	-	EN301 MF	-	D; B(t)
[62] 6)	≤3(18)/≤1.25/ 60÷300	60÷240/12÷40 TL *w*/*t*≥2.4	≥C24 ≥GL24	>>	-	-	1K-PUR	-	-
[63] 6)	≤3(18)/≤1.25/ 60÷300	60÷240/12÷40 TL *w*/*t*≥2.4	SW ≥C24 ≥GL24	>>			EN301	-	D; FJ; LFJ; BS
[64]	≤18/≤3/36÷280 3÷13 layers	70÷280/12÷40 TL *w*/*t*≥4	SW C16-C35	2(4)	N	N	EN301 EN15425 MUF	-	-
[65]	≤18/≤3/36÷280 3÷7 layers	70÷220/12÷40 TL *w*/*t*≥4	SW ≥C16	4	-	-	EN301 MUF	-	RS or Sh; D; FJ

[66]	≤5/≤1.25(24)/60÷350 ≥3 layers	80÷250/18÷45 TL w/t≥4	SW C16/C24	TL 2 LL 0	Y	LL Y	EN301 SP: MUF 1K-PUR	-	-
[48]	large elements ≤22/≤3.5/51÷215 system format ≤5/≤1.25(24)/54÷350	large elements 100÷200/17÷43 system format 80÷250/18÷45 TL w/t≥4	SW C16/C24	4	Y	Y/N	EN301 SP: MUF 1K-PUR	large elements vacuum 80÷90 kPa system format hydraulic	RS or Sh; D; FJ; LFJ
[67]	≤18/≤3.5/60÷400 3÷11 layers	LL 80÷260/15÷45 TL 80÷260/15÷40 TL w/t≥4 solid wood panels -/15÷45	S,P,F,L	LL 3 TL 6	Y/N	N	EN301 MUF	pneumatic 0.5÷0.8 MPa	-
[68]	≤16.5/≤3/42÷350 3÷20 layers	40÷300/14÷45 TL w/t≥4 solid wood panels (TL) 250÷1,600/-	S,P,F ≥C16	2(4)	pos.	pos. TL Y	EN301 EN15425 SP: EPI 1K-PUR	-	-
[53]	≤16.5/≤3/42÷500 3÷27 layers	40÷300/14÷45 TL *w*/*t*≥4 solid wood panels (TL) 250÷1,600/-	SW ≥C16	2(4)	pos.	pos. TL Y	EN301 SP: EPI 1K-PUR	-	RS; DL, D or BS; FJ
[69]	≤16.5/≤2.95/57÷250 3÷9 layers	80÷240/10÷40 TL *w*/*t*≥4	S ≥C16	3(6)	-	-	EN301 1K-PUR	hydraulic ≥0.6 MPa	-
[70]	≤16.5/≤3/57÷500 3÷27 layers	80÷240/10÷40 TL *w*/*t*≥4	S ≥C16	3(6)	-	-	EN301 1K-PUR	-	RS; D; FJ
[10]	≤16/≤3.2/50÷300 ≥3 layers	80÷200/18÷40 TL *w*/*t*≥4	S,P,D T*l* C24 C*l* C16	6	-	-	EN301 1K-PUR	-	RS or Sh; D; FJ
[35]	≤6/≤3.25/≤345 ≥3 layers	140÷260/23	SW ≥C16	-	-	-	EN301	ring shank nails	FJ
[71]	≤18/≤3/60÷300 3÷9 layers	LL 80÷240/20÷80 TL 80÷240/20÷40 TL *w*/*t*≥4	S,P,F,L, D ≥C16	LL 3 TL 6	-	-	EN301 EN15425	hydraulic 0.6 MPa	-
[72]5)	3L -/-/13÷49 5L -/-/27÷42 3 or 5 layers	3L: T*l* 91÷190/4.5÷12 C*l* 44÷150/4÷25 5L: T*l* 117÷190/4.5÷8.5 C*l* 44÷150/5÷9	≥C16	-	-	TL Y	approval	-	D; B(t)
[49]	≤20/≤4/45÷280 3÷7 layers	40÷300/15÷40 TL *w*/*t*≥4	SW ≥C16	2(4)	pos.	pos.	EN301	vacuum 80÷90 kPa	RS or Sh; D; FJ
[33]	≤20/≤2.5/60÷200 ≥3 layers	80÷160/20÷40	SW T*l* ≥C24 C*l* ≥C16	-	-	-	EN301 1K-PUR	vacuum 80÷90 kPa	RS; D; FJ
[36]	≤10/≤3/≤400 orientation 90°, 45° or 0°	≥100/24÷60	SW ≥C16	10	-	-	-	hardwood dowels *d*=20 mm	-
[73]	≤15.5/≤3.45/27÷210 3÷7 layers	60÷300/9÷30 TL *w*/*t*≥4	S,F C16÷C30	2(4)	-	LL pos.	EN301	-	D or BS; FJ

[74]	≤20/≤4/57÷280 3 or 5 layers	80÷200/19÷45 TL w/t≥4	S or sim. ≥C16	3	pos.	LL pos.	EN301 MUF	-	-
1)	BM … base material; SP … single-layer panel; TL … transverse layers; LL … longitudinal layers; T*l* … top layer; C*l* … core layers; *w* … width; *t* … thickness								
2)	SW … softwood species; S … Norway spruce; P … Scots pine; F … White fir; L … European larch; D … Douglas fir; sim. … similar timber species strength class according to EN 338 [8] (or EN 1194 [28], prEN 14080 [13])								
3)	data of technical approvals complemented by manufacture's data (product leaflet, reports, etc.); adhesives according EN 301 [26] only of type I								
4)	RS … rolling shear of CLT; BS … block shear CLT; FJ … finger joint; DL … delamination CLT; D … delamination (dispartment at glue line) according to DIN 53255 [54]; B(t) … transverse third-point bending; Sh … (rolling) shear test								
5)	3- or 5-layers wood panels for load bearing purposes								
6)	dissolved cross laminated timber products for load bearing purposes								

5. Discussion and conclusion

This paper provides an overview of current production techniques for cross laminated timber (CLT). The focus is on industrial production lines, although also productions for small and median scaled producers are concerned. The work aims on CLT as rigid composite, composed of cross-wise arranged and surface bonded layers of boards or single-layer panels.

To summarise in brief it can be said that currently and in regard to the production volume of CLT the hydraulic press facilities are dominating. Their further gain in market share, in particular concerning large productions with automated lines is expected and supported by the meanwhile offered modular press and production systems. Of course no clear trend regarding the production parameter "edge bonding" has been observed yet. In fact, the gain by edge bonding concerning building physics and connection technique (e.g. in case of pin-shaped fasteners) has to be questioned since the occurrence of checks, as a consequence of swelling and shrinkage due to the exposition of CLT to cyclic climatic conditions, cannot be avoided. Thus producers aim on reducing the gap widths between boards or single-layer panels within the CLT layers. Latest developments in press technology allow the application of lateral pressure individually on all CLT layers. This enables to produce CLT elements with gap widths of zero, but without edge bonding. Furthermore there is a trend that machine manufacturers offer their facilities together with CLT production licences (e.g. woodtec Fankhauser GmbH / CH with [33]; Hans Hundegger Maschinenbau GmbH / DE with [35]).

Further distribution of CLT results in the indispensability of standardised regulations not only in Europe, but worldwide. First important steps in this regard are in process, e.g. the product standard prEN 16351 [1] for CLT and the efforts in harmonising the lamella thickness with $t_L = (20, 30, 40)$ mm. Further steps, in particular concerning the design procedures, the detailing (building physics; leading details; structural engineering) and joining technique are required.

The product CLT provides not only timber engineering, but also the whole building sector with new possibilities and offers new horizons. Currently the potential of CLT is seen in multi-storey timber constructions for office and residential buildings and thus may initiate a Renaissance of timber engineering in our cities. To improve its economics in particular in competition to mineral building materials like reinforced steel, masonry and steel structures, the development of CLT building systems and, consequently, the establishment of the solid timber construction technique with CLT are seen as the next mile stone (see also the four-year research project "focus_sts" at the competence centre holz.bau forschungs gmbh / AT). Therefore it is a must to take care of the peculiarities of timber as building material, in particular its vulnerability in context with moisture.

As a consequence of the establishment of a building system, a vertical extension of CLT production lines by assembling stations is expected. Within these stations whole wall and ceiling elements including not only windows, doors and installations, but also the finale facade system with insulation, as known from current production lines for light-weight timber constructions, can be readily processed. Another possibility is to prefabricate plug-and-play facade modules. Parallel to this, the increase of establishing engineering offices directly at, or rather in close cooperation with, CLT producers is prognosticated.

Thereby the solid timber construction technique with CLT is not regarded as competitor against the existing timber building sector with focus on linear timber elements. Building technique with CLT has already shown to open and extend the possibilities to realise structures in timber. In fact, meanwhile CLT is in direct competition with mineral based solid building materials, like reinforced concrete and masonry. Further extension of this position is expected. This is in particular enforced by the circumstance that the product CLT has only minor requirements regarding the mechanical potential of the basic material. So far minimum principles as mentioned in this contribution are applied. Thus also local timber species can be sustainably utilised and value can be gained regionally, which may lead to the worldwide establishment of CLT. Consequently, the creation of further small and median scaled production lines and companies as well as of some big players worldwide all operating in the field of CLT is expected.

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