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CLTdesigner – A SOFTWARE TOOL FOR DESIGNING CROSS LAMINATED TIMBER ELEMENTS: 1D-PLATE-DESIGN

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ABSTRACT: In the last few years the engineered building product cross laminated timber (CLT) has become very common in timber engineering applications – in particular as ceiling and wall elements in single- and multi-storey buildings. In order to provide save and reliable design guidelines numerous design concepts have been developed. Especially for the 1D-plate design of CLT, as discussed in this paper, references are made to the “bearing model for CLT-plates in bending” given in [1], which takes into account parallel system effects and laminating effects as well. This model has been already implicit anchored in technical approvals for CLT and implemented in the herein presented CLTdesigner. This software tool does the essential verification of bending and shear stresses for the ultimate limit state (ULS) for persistent, transient and accidental (fire) design situations, as well as for the verification of deformation and vibration in case of serviceability limit state (SLS) design according to the European standard EN 1990 and EN 1995. This software tool shall be able to simplify the design process of CLT for engineers and master carpenters in practice, and stimulate the wider application of CLT.

KEYWORDS: CLT, cross laminated timber, design verification process, software tool, 1D-design of CLT-plates

1 INTRODUCTION

The application of CLT, typically as two-dimensional elements, like ceilings and walls, has been very common in modern timber engineering structures. CLT-elements represent multi-layer plate structures consisting of a sequence of board layers with alternating orthogonal orientation of neighbouring board layers (Figure 1). The stacking sequence of the layers in thickness direction is usually symmetric with respect to the plate mid-plane. The boards of each single layer are usually arranged side-by-side and can be glued together on the narrow face. CLT-elements are available 3- to 9-layered. Commonly 3- and 5-layered elements are used for walls, 5- and 7-layered ones for ceilings and 9-layered ones for special high-bearing purposes. The thickness of each layer lies in between 6 and 45 mm.

In order to provide save and reliable design guidelines numerous design concepts have been developed, e.g. analytically exact solutions of shear flexible multi-layered plates [2, 3], the so called method of “shear analogy” (SAV) [4], which is implemented in the design codes of Germany DIN 1052:2004 [5] and DIN 1052:2008 [6], the modified Gamma-method [7] and the “bearing model for CLT-plates in bending”, which was first introduced at CIB - W18 in 2006 [8]. Nevertheless all these methods are very time-consuming in practice and due to approximations deviating from the exact mechanical solution [2, 3].

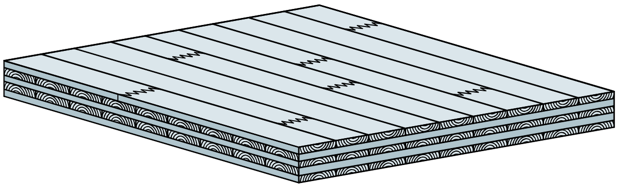

***Figure 1:** 5-layered CLT-element*

For simplification of the design and for stimulating of wider application of CLT-elements the verification process given in [1], which is practicable adequate, traceable and easily capable by engineers and master carpenters in practice, was implemented into the software-tool CLTdesigner.

2 PROGRAM ARCHITECTURE

The CLTdesigner, organised in modules, is written in the object oriented programming language. For the verification of CLT-plates under loads out of plane there are two modules implemented. The first module “ContinuousBeam” verifies CLT-plates according to EN 1995-1-1 [9] and ON B 1995-1-1 [10], as a continuous beam up to 7 spans with or without cantilevers. The CLT-plate can be subjected to self- and

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construction weight, imposed load, snow and wind load. The ultimate limit state design (ULS) is provided in respect of bending and shear stresses as well as compression stresses perpendicular to grain for combinations of actions for persistent or transient and accidental (fire) design situations. The serviceability limit state design (SLS) is made in respect of deformations and vibrations.

The second module “CSVerification” provides a cross-sectional verification of CLT-elements depending on given internal forces and moments as well as a stability verification tool based on the model column method. Each of these base-modules contains several reusable sub-modules. The important ones are listed in Figure 2, including sub-modules for calculating section properties, creating the reduced cross section for structural fire design, discretication of the structure, calculating internal forces and moments as well as deformations and reaction forces. Further sub-modules are for automatically creating and calculating the combinations of actions, for calculations in context with vibrations, as well as one for the final verification process itself.

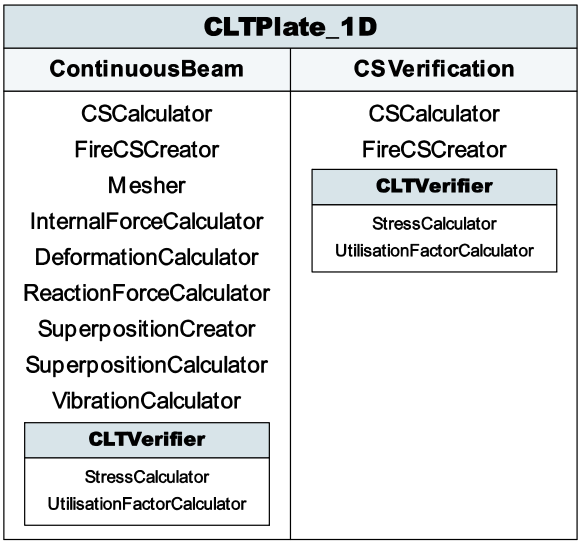

***Figure 2:** Base- and sub-modules of the CLTdesigner*

The implemented verification process, its principles and scope are presented in the next chapters.

3 PRINCIPLES OF DESIGN VERIFICATION AND SCOPE

Because of geometric relations within the CLT-element and geometric boundary conditions nowadays produced CLT-plates show a main load carrying direction. Therefore 1D-beam theory sufficiently represents the bearing behavior of CLT-plates for practical applications and is applied for calculating stresses and deformations. Nevertheless, compared to uni-axial layered products like glue laminated timber (GLT), due to low rolling shear modulus of cross layers, CLT-elements show remarkable deformations. Therefore shear deformation shall be taken into account in case of deformation calculation.

A comparison of the different design methods for cross-layered plates mentioned above with an exact solution, reflects that all of them provide suitable solutions for practically relevant length to depth ratios $L/H > 15$, but deviating from the exact solution. Due to these deviations, shown in Figure 3, the following procedure will be recommended:

- For $L/H < 15$ the analytically exact solution of shear deformable multi layer beam is required.
- For $L/H \geq 15$ every one of the approximated models mentioned above seem practicable applicable, except Euler-Bernoulli beam theory which neglects shear deformations, but it is strongly recommended that the chosen method for the design of CLT-plates is congruent with the evaluation of strength and stiffness in testing procedures. Nevertheless, standardised testing procedures for CLT in general are lacking.

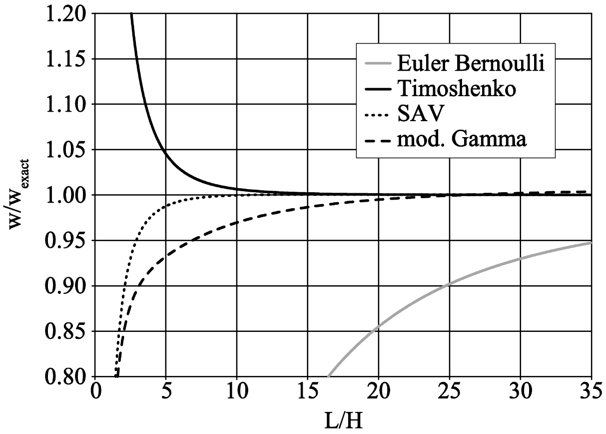

***Figure 3:** Deformations calculated by means of various methods in relation to the exact analytical solution of a 5-layered CLT-element with thickness relation $t_{90}/t_0=1.0$*

The implemented method in the CLTdesigner is based on the Timoshenko beam theory considering a transversal shear flexible beam. A comparison of this method with the exact solution of [3] reflects the dependency of the results from the thickness ratio t_{90}/t_0, where t_{90} is the thickness of cross layers and t_0 the thickness of longitudinal layers. Therefore, this ratio of CLT-elements produced nowadays were analysed and the results are shown in Figure 4. The ratio is varying from 0.45 to 2.10, with a mean value near 1.00.

The deviations of the proposed method from the exact solution are lower for deformations than for stresses and dependent on the number of layers, the arrangement and thickness ratio t_{90}/t_0. Figure 5 shows the deviations in case of a 5-layered CLT-element for deformation w, normal stress σ in the edge layer, maximum shear stress τ_0 in the layer with $\alpha = 0°$ and maximum shear stress τ_{90} in the cross layer for various thickness ratios $t_{90}/t_0 = 0.5 \div 3.0$.

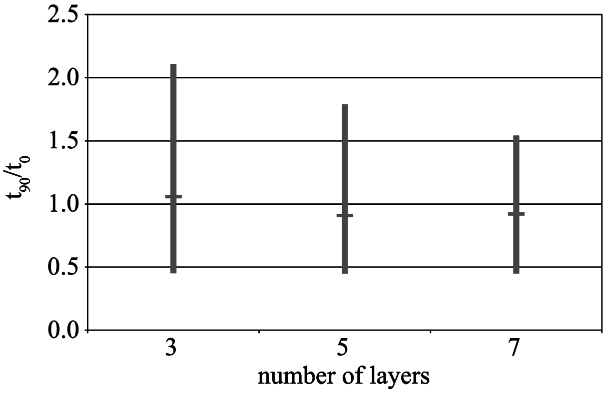

Figure 4: *Range (min – max) and mean values of thickness ratio t_{90}/t_0 of current available 3-, 5- and 7-layered CLT-elements*

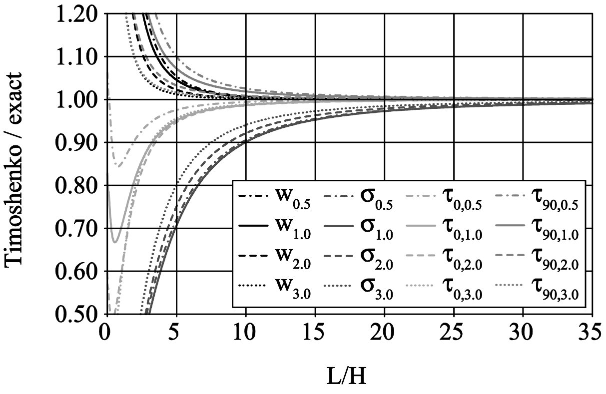

Figure 5: *Deformations and stresses calculated on Timoshenko beam theory in relation to the exact solution of a 5-layered CLT-element: $t_{90}/t_0 = 0.5 \div 3.0$*

The same comparison is done for 3- and 7-layered CLT-elements and therefore a deviation field can be stated (Figure 6).

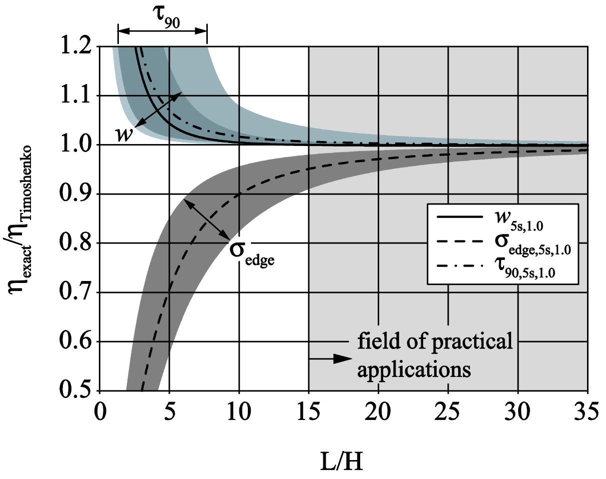

Figure 6: *Deformations and stresses calculated on Timoshenko beam theory and its range of deviation from the exact solution depending on number of layers (3, 5 and 7) and thickness ratio $t_{90}/t_0 = 0.5 \div 3.0$*

The largest deviation from the exact solution is given by normal stress σ in case of a 3-layered CLT-element. The deviation at L/H = 15 is about 9 %. Nevertheless in case of congruent evaluation of strength and stiffness values by tests by means of the Timoshenko beam theory, this deviation will be reduced. For practical applications the provided accuracy seems to be sufficient. In case of L/H < 15 the utilisation factor of normal stresses is normally not decisive for the design process.

3.1 Bending stiffness

The bending stiffness K_{clt} of a CLT cross section will be calculated according to equation (1). Thereby the changing layer orientation and corresponding material parameters like the Youngs modulus have to be taken into account. For layers with $\alpha = 0°$ the Youngs modulus E_0, and for layers with $\alpha = 90°$ the Youngs modulus E_{90} shall be applied. The ratio E_0/E_{90} is 30 (see EN 338) leading low (minor) share of bending stiffness provided by the cross layers which can as approximation neglected in calculation ($E_{90} = 0$).

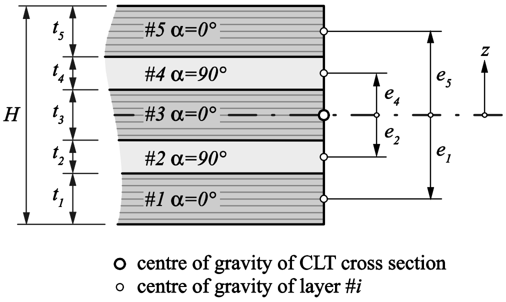

Figure 7: *5-layered CLT cross section*

$$K_{\mathrm{clt}} = \sum (J_i \cdot E_i) + \sum (A_i \cdot e_i^2 \cdot E_i) \tag{1}$$

where J_i = moment of inertia of layer i computed in reference to the neutral axis of layer i, E_i = Youngs modulus of layer i, A_i = area of layer i, e_i = distance between neutral axis of layer i to neutral axis of CLT cross section.

3.2 Shear stiffness

The shear stiffness S_{clt} of CLT cross sections is depending on the shear stiffness of a composite beam without warping of cross-sectional area S_{ges} according to equation (3) and the shear correction coefficient κ according to equation (4). For the cross layers the shear modulus perpendicular to grain G_{9090} (rolling shear modulus) has to be used instead of the shear modulus G_{090}.

$$S_{\mathrm{clt}} = S_{\mathrm{ges}} \cdot \kappa \tag{2}$$

$$S_{\mathrm{ges}} = \sum (G_i \cdot b_i \cdot t_i) = \sum (G_i \cdot A_i) \tag{3}$$

$$\kappa = \frac{1}{S_{\text{ges}} \cdot \frac{1}{K_{\text{clt}}^2} \cdot \int_h \frac{S^2(z, E(z))}{G(z) \cdot b(z)} \mathrm{d}z} \tag{4}$$

where G_i = shear modulus of layer i, t_i = thickness of layer i, b_i = width of layer i, $S(z,E(z))$ = first moment of area depending on coordinate z, $G(z)$ = shear modulus depending on z, $b(z)$ = width of cross section depending on z.

The calculation of shear stiffness and shear correction coefficient, as implemented in the CLTdesigner, is done by numerical integration over the whole cross section. In Figure 8 results of the implemented CLT-products are shown and compared to the analytical solutions. Due to the influence of the transversal shear flexible cross layers, the shear correction coefficient of a CLT-element is in the current product-range nearly constant and about ¼ of unidirectional rectangular cross section.

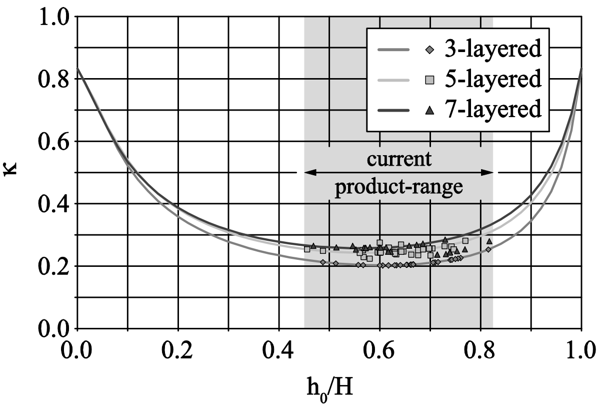

Figure 8: *Shear correction coefficient for the ratio G_{090}/G_{9090} = 10 depending on depth ratio h_0/H – analytical solution and current products evaluated by means of the CLTdesigner, where h_0 is the sum of thickness of all layers with α = 0°.*

4 DESIGN VERIFICATION PROCESS

4.1 ULTIMATE LIMIT STATES (ULS)

In Timoshenko beam theory the Bernoulli-hypothesis of plane remaining cross section during deformation is still implemented. Therefore, the bending stress distribution over the cross section remains also linear.

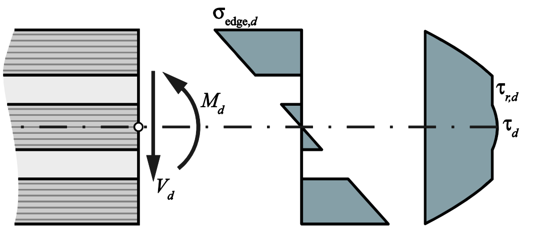

Figure 9: *Stress distribution over cross section of a CLT-plate due to bending moment and shear force (E_{90} = 0)*

4.1.1 Bending

For verification of bending, equation (5) shall be fulfilled. Therefore, the bending stress on the edge $\sigma_{edge,d}$ according to equation (6), with $z = H/2$ in case of symmetrically CLT cross sections, and the design value of bending strength of CLT $f_{m,clt,d}$ according to equation (7) are required.

$$\frac{\sigma_{edge,d}}{f_{m,clt,d}} \leq 1.0 \tag{5}$$

$$\sigma(z) = \frac{M_y}{K_{\text{clt}}} \cdot z \cdot E(z) \tag{6}$$

$$f_{m,clt,d} = k_l \cdot \frac{k_{\text{mod}} \cdot f_{m,glt,k}}{\gamma_M} \tag{7}$$

where M_y = bending moment about y-axis, k_l = system strength factor, k_{mod} = modification factor for duration of load and moisture content, γ_M = partial safety factor for material properties and $f_{m,glt,k}$ = characteristic bending strength of GLT of appropriate strength class with reference depth of 600 mm.

The system strength factor k_l has to be calculated according to equation (8), depending on the number of parallel interacting boards n in the edge layer of tension zone. The width of a board can vary from 80 to 250 mm. The implemented reference board width in the CLTdesigner is 250 mm and therefore the calculated system factor will be on the safe side. This equation can also be found in some technical approvals like [12-14].

$$k_l = \min \begin{cases} 1.1 \\ 1 + 0.025 \cdot n \end{cases} \quad \text{for } n > 1 \tag{8}$$

4.1.2 Shear

For shear design two verifications have to be fulfilled (see equation (10)). Beside the classical procedure for unidirectional layered cross sections, also a proof of shear stresses in cross layers vs. the rolling shear strength has to be done. The shear stresses are herein calculated according to equation (9).

$$\tau(z_0) = \frac{V_z \cdot \int_{A_0} E(z) \cdot z \cdot \mathrm{d}A}{K_{\text{clt}} \cdot b(z_0)} \tag{9}$$

The design values of shear strength and rolling shear strength will be the same as for GLT of appropriate strength class.

$$\frac{\tau_d}{f_{v,clt,d}} \leq 1.0 \quad \text{and} \quad \frac{\tau_{r,d}}{f_{r,clt,d}} \leq 1.0 \tag{10}$$

4.2 STRUCTURAL FIRE DESIGN

The implemented structural fire design is described e.g. by Frangi in [1] and is based on the method of reduced cross sections according to EN 1995-1-2 [15]. Therefore, the information about charring depth d_{char} over the time is decisive. The charring depth depends on the charring rate (layers with or without gaps between boards), the type of adhesive applied (high temperature proof or not) and on the availability of fire protection.

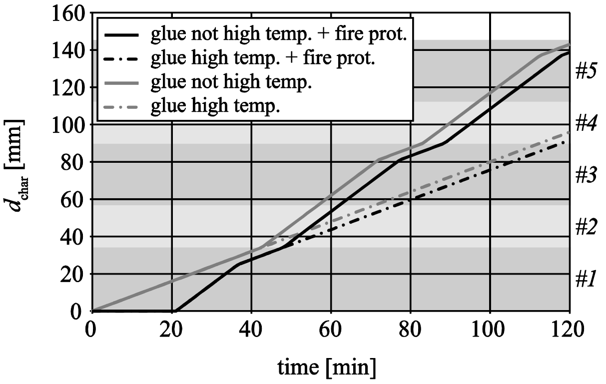

Figure 10: Charring depth in time-dependency on type of adhesive and availability of fire protection.

The definitions of the reduced cross section are given in Figure 11. The depth is reduced by the effective charring depth d_{ef} according to equation (11), where k_0 increase linear from 0 to 1 in the first 20 min of fire impact. That means that after a fire time t of 20 min the full additional thickness of $d_0 = 7$ mm, which is considering the zone of thermal modified material parameters, is added to the charring depth.

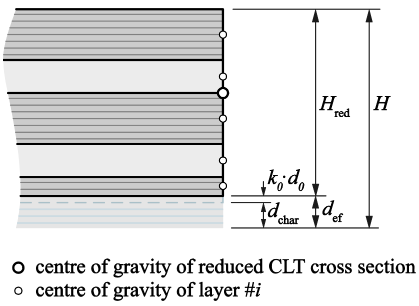

Figure 11: Definitions of reduced cross section due to fire

$$d_{\text{ef}} = d_{\text{char}} + k_0 \cdot d_0 \quad \text{with} \quad k_0 = \min \begin{cases} t/20 \\ 1.0 \end{cases} \tag{11}$$

By means of calculated reduced cross sections the verification process in case of fire can be done in the same way as described in 4.1, but considering the design strength in fire $f_{d,fi}$ according to equation (12). Because of fire as accidental design situation, the 20%-fractile of strengths f_{20} can be applied.

$$f_{d,fi} = k_{\text{mod},fi} \cdot \frac{f_{20}}{\gamma_{M,fi}} \quad \text{with} \quad f_{20} = k_{fi} \cdot f_k \tag{12}$$

where $k_{\text{mod},fi} = 1.0$, $\gamma_{M,fi} = 1.0$ and $k_{fi}=1.15$

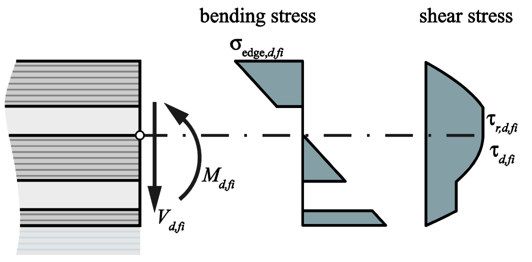

Figure 12: Stress distribution over cross section due bending moment and shear force in case of fire ($E_{90} = 0$)

The design calculations can lead to remain border layers of less than 6 mm thickness which are due to its position relative to the neutral axis, supposed to higher bending stresses on the edge as in case of neglecting the remaining thin layers. Therefore, the fire design procedure implemented in the CLTdesigner neglects thin layers with thickness < 6 mm.

4.3 SERVICEABILITY LIMIT STATES (SLS)

4.3.1 Deflections

The deflections due to bending moment and shear force at time t=0 can be calculated according to equation (13). For long time effects the deformation factor k_{def} shall be considered. Detailed information about the deformation factor of CLT-elements is given in [11]. The proposed and implemented values are $k_{\text{def}} = 0.85$ for service class 1 and $k_{\text{def}} = 1.1$ for service class 2.

$$w_{\text{ges}} = \frac{1}{K_{\text{clt}}} \int \left(M \cdot \overline{M} \right) \mathrm{d}x + \frac{1}{S_{\text{clt}}} \int \left(V \cdot \overline{V} \right) \mathrm{d}x \tag{13}$$

The implemented combinations of actions and limits are according to the regulations in [9] and [10].

4.3.2 Vibrations

According to EN 1995-1-1 [9] four criteria have to be verified for judging vibration behaviour of a CLT-plate. First of all the first eigenfrequency has to be calculated. The implemented method considers the deformation based evaluation of the eigenfrequency by Morleigh, as described in [16]. Secondly a stiffness criterion has to be calculated whereby the maximum instantaneous deflection caused by a concentrated static force of 1kN is limited. The third proof involves the vibration velocity. The last verification evaluates the vibration acceleration. The implemented equations are described in detail in [1]. The examination of the very important damping factor for ceilings of CLT-elements can be found in [18].

5 CONCLUSIONS

The software tool CLTdesigner provides the design verification process of CLT-elements loaded out of plane more or less fully automated and therefore should stimulate, simplify and support its wide application. Nevertheless the development of the CLTdesigner is still in process. The next steps are the implementation of a module for verification of CLT-elements under loads in plane and a further module covering the verification process of conventional connection types of CLT-elements. For information about the current state see [19].

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