ON SELECTED DIRECTIONS OF IMPROVEMENT IN METHOD OF DESIGN OF TIMBER STRUCTURES

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Summary:
Durability of timber structures depends on quality of design, conditions of manufacturing, transportation, assembling and exploitation. Any depart from the standard principle and requirements at any stage of structure preparation, as well as any abandon of specifications leads to commencement and progress of defects in the structure in process of exploitation and finally it causes the decrease of durability and sustainability and in effect decrease of life-service time. Load bearing capacity of timber structures decreases in time. Influence of load lasting time on strength parameters of timber derivative materials, and conditions of exploitation and common load action are included in application of partial modification factor k_{mod}, which was obtained in empirical way basing on experience of timber structure exploitation and wood parameters. This coefficient does not take into account state of stressing in structural element (bending, compression, tension parallel to the grain or perpendicular to the grain or shear). Wood considered as a solid body, undergoes failure in result of accumulation of sub-micro-defects. Factor k_{mod} in case of wood under static constant load tension perpendicular to grain within 50 years for service class 1 will give value of 0,15 what is four time lower than given in EN 1995. Work also consider some glulam defects and cracking under varying load action in the structures. Connections in glulam structures shall be designed to transfer the design load to and from structural element without causing local stress concentrations. These local stresses may initiate failure in the connection and then failure of whole structure. It is also important to design the connections isolating all timber elements from potential sources of potential moisture. The next part of the work refers to the cross laminated timber CLT as a new wood technology. This technology may soon open up the construction sector to wood building. There presented characteristic parameters of CLT and principles of design of modern timber structure using this new material.

Keywords: glulam, durability, cracks, cross laminated timber

Improvement in methods of design

Exploitation practice of timber structure specifically glued laminated timber (glulam) shows, that these structures not always fulfill conditions of durability and sustainability (long-life service) (Jasieńko 2003), (Kotwica et al. 2011), (Miedziałowski, Malesza 2006) due to varying natural wood defects, creation of cracks parallel to grain, delamination, splitting effect, deterioration in result of fungi, insects, bacterial or chemical attacks and weathering. It is known that within exploitation process is noticed lost of physical and functional wearing of timber structure. Lost of physical ability and wearing of timber structures become a main reasons leading to reconstruction and is resulted from physical, chemical and biological action on structures. All these action are taken into account in process of timber structure

design adopting requirements stated in standard documents and specifications. For this reason durability of timber structures depends on quality of design, conditions of manufacturing, transportation, assembling and exploitation. Any depart from the standard principle and requirements at any stage of structure preparation, as well as any abandon of specifications leads to commencement and progress of defects in the structure in process of exploitation and finally it causes the decrease of durability and sustainability and in effect decrease of life-service time. It is widely known, that load bearing capacity of timber structures decreases in time depending on type and time of loading, conditions of exploitation and kind of material.

In the EC countries and in some Custom Union Countries-СНГ (Republic of Belarus, Kazakhstan, Ukraine) process of design of timber structures is conducted with accordance to adequate recommendations and requirements. According to (EN 1992) influence of load lasting time on strength parameters of timber derivative materials, as well as conditions of exploitation and common load action are included in application of partial modification factor k_{mod}, which was obtained in empirical way basing on experience of timber structure exploitation and wood parameters. The most acceptable approach in evaluation of k_{mod} has been described in work (Sorensen et al. 2005). This approach is based on the probability models securing the load bearing capacity of structure. Evaluation of these models is based on accumulation of defects according to Gerhardsa (Gerhards 1972), Barretta and Fosghi (Barrett, Foschi 1978) also Foschi and Yao (Foschi, Folz 1989). Indicated models are used for mathematic description for decrease of the load bearing capacity under sustained (long lasting) load in the form of function of load value and time of its application. Analyzing meaning of k_{mod} factor given in (EN 1992) it can be noticed, that this coefficient does not take into account state of stressing in structural element (bending, compression, tension parallel to the grain or perpendicular to the grain or shear). In our opinion this approach on evaluation of long-time duration of load influence on the wood strength parameters not completely includes specific of wood behavior. It is very well known, that wood, including also polymers considered physically as a solid body, undergoes failure in result of accumulation of sub-micro-defects. In this way equation of long-life of wood corresponding to concept of kinetic strength of solid body (EN 1992) can be described in the form:

$$t = \tau_0 \cdot e^{\frac{U_0 - \gamma \cdot \sigma}{R \cdot T}} \tag{1}$$

or

$$\lg t = \lg A - \alpha \cdot \sigma \tag{2}$$

where

$$\alpha = \frac{\gamma}{2{,}3 \cdot R \cdot T} \quad ; \quad \lg A = \frac{U_0}{2{,}3 \cdot R \cdot T} + \lg \tau_0 \tag{3}$$

U_0 – initial energy of activation in process of failure in kJ/mole
t_0 – period of atom thermal vibration, c;
s - stress, MPa;
t – time to failure (long-life), c;
γ – structure-чувствительный coefficient, kJ/[mole x MPa];
R – characteristic of thermal movement (gas constant) , KJ/(mole x grad);
T – temperature, K.

In result of conducted analysis of experimental data on the base of principle equation of the kinetic concept of solid body strength according to Ivanov J.M. (Ivanov 1986), two mechanisms of failure for wood were discovered, which are strongly varying within time t up to destruction. Hence, for different timber materials under tensile, compression or shear stresses along the grain (Ivanov 1981), segment in varying tests under long-lasting load, being cut-off of the long term strength of wood from formula {2} along coordinate *lg t*, equal 17,1, while under tension perpendicular to the grain it is equal 10,214 (Ivanov 1986) (Fig.1). In case of tension of wood under 45^0 to grain direction according to investigation in (Orlowicz, Naiczuk 1989-1), value of sectioned segment along coordinate *lg t* is 15,1. Using obtained results meaning of k_{mod} in case of wood under static constant load tension perpendicular to grain within 50 years for service class 1 will give value of 0,15 what is four time lower than given in (Zurkov 1957). In this way, fulfilling calibration of k_{mod} parameter in probability models shall take into account properties of failure of wood depending on type and conditions of stressing.

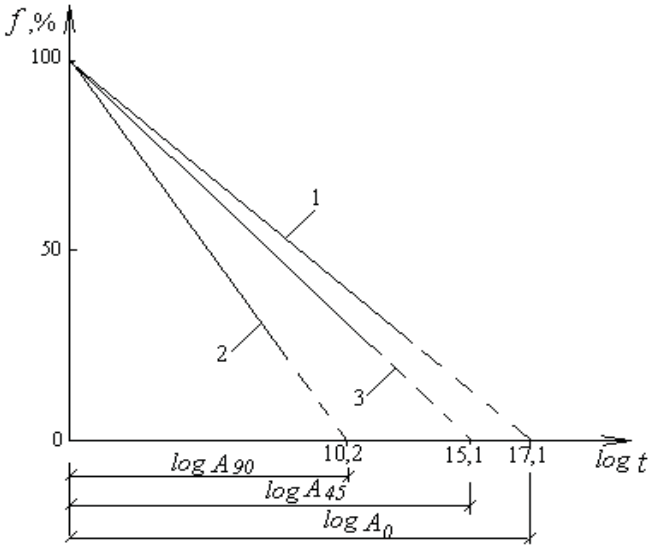


Fig.1. Dependence of long-term strength of wood under varying kind of stressing: 1-tension, compression and shear along the grain, 2-tension perpendicular to grain, 3-tension under 45 deg. to grain

Solution of this task is specifically actual for cases of evaluation of wood strength in the structure working in combined stressing conditions, taking into account criterial dependencies. Except this, in evaluation of technical state of timber structure with defects in the form of surface cracks, we are very often facing the question about evaluation of the final resources. Linking here methods of the failure mechanics in evaluation of the load bearing capacity or final resources of the structure with defects in the form of surface or sectional cracks is impossible without solving questions referring evaluation of formula depending changes of viscosity in failure of wood (velocity of freeing energy)

and form of failure and time of load lasting. It shall be noticed, that adopted in calibration of k_{mod} probabilistic models, and evaluation of their meaning at the same time can be used in evaluation of design strength and viscosity of failure of wood in the design of timber structure. As far as the use of their in evaluation of technical state (evaluation of final resources) is concerned, their application in our opinion is incorrect. In this case probably (if wood is not biologically defected) shall be used models basing on equation of kinetic concept of strength and principle of the linear summing of defects, where according to (Orlowicz, Naiczuk 1989-2) independence of final strength of wood in the function of loading has been stated. At the same time, action on structure within gone period of structure exploitation should be taken on the information and data of meteorological service for considered region.

In (EN 1992) analysis of at-supporting parts of timber beams under action of shear force Q shall be conducted with application of surface cracks. In this case effective (design) wide of cross-section in computer from formula

$$b_{ef} = k_{cr} \cdot b \tag{4}$$

where b_{ef} – effective (design) width of the cross-section of beam,
b – width of the beam cross-section,
k_{cr} – coefficient, for solid wood or glulam wood is taken in value of 0,67.

This requirement does not give the answer on the following questions: what shall be the surface cracks, one- or both-sides, what is the allowed depth b_{cr} *and the length* l_{cr} of the crack, how shall be accounted possible number of surface cracks and their geometry parameters (b_{cr}, l_{cr}) in analysis of beam under torsion load. According to given in (EN 1992) requirements additional investigations are to be conducted on specifying or evaluation of the load bearing capacity of the at-supporting sections of beam with defects in the form of surface cracking depending on geometric parameters crack itself and cross-sectional dimensions of beam (height h and span L). As far as the surface cracks are concerned, it shall be noticed, that at the supporting segments of the beams more of then for any other reasons, the cracks are appearing in result of cyclic temperature-moisture action in the process of exploitation due to improper isolation of beam end against moisture. Strength sectional cracks may appear in timber glulam beams if $h/b>4$, at the distance $0{,}5h$ from the support and at the distance on the height of section $0{,}15h$ - $0{,}2h$ from neutral axis towards the tensile zone (Serov et al. 2010).

Influence of improper connections on creation of cracks and splitting in glulam elements – selected examples (Fruhval et al. 2007), (APA 2007)

Proper connection details are important to structural load bearing capacity and serviceability on any kind of timber framed structure constructed of solid or glulam wood. In case of longer span and larger cross section dimensions usually constructed as the glulam elements proper detailing connections is more critical than in case of solid wood elements. Consideration on the stage of design the moisture-related expansion and contraction characteristics of wood is essential in detailing glulam connections to prevent inducing tension perpendicular to grain stresses. Always in structure connections are to

be designed to transfer the design load to and from structural element without causing local stress concentrations. These local stresses may initiate failure in the connection and then failure of whole structure. It is also important to design the connections isolating all timber elements from potential sources of potential moisture. Wood expands in result of changes in its internal moisture content. In designing connections for glulam structure shrinkage effect cannot be restrained. In case of restrained shrinkage causing exceeding tension perpendicular to the grain stresses may cause split parallel do grain. Splitting failure reduces greatly shear and bending capacity of glulam elements. Improper beam notching can induce internal moment and tension stresses perpendicular to the grain.

There are several basic principles being leading to efficient, durable and structurally sound connections (APA 2007):

- load shall be transferred in compression bearing whenever possible,
- in glulam shall be allowed dimensional changes due to potential moisture cycling,
- details of connections inducing tension stresses perpendicular to grain shall be avoided,
- avoid moisture entrap in connection,
- glulam element shall not be placed in direct contact with masonry and concrete,
- eccentricity in joints details shall be diminished

Selected examples of improper detailing leading to failure and defects in connections:

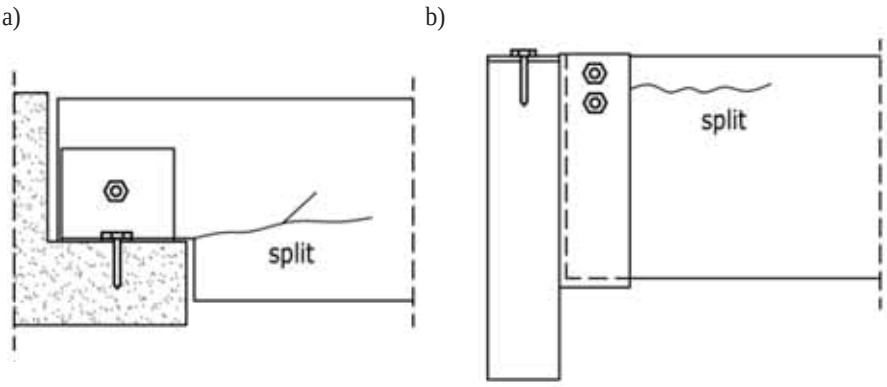


Fig. 2. a) Notching at the end of beam, b) Beam-to-beam connections

Notching at the end of beam can lead to splitting at inside corner due to shear stress concentrations and induced tensile stresses perpendicular to grain. The notch cannot exceed of 1/10 of the beam depth and result of lateral restrain at the top of the glulam beam, shrinkage of the beam can cause splitting at the top of connection because load is transferred from the bearing seat to connecting bolt. Splitting can occur also when restrain does not allow the beam for rotation in result of deflection.

Beam-to-beam connections. Shrinkage of supported beam causes bearing load to transfer from beam saddle to fasteners, causing splitting of beam.

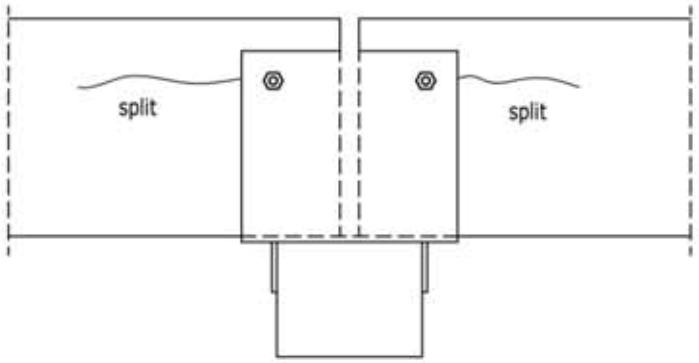


Fig.3. Splice steel plates applied to both sides of members may cause splitting if members shrink. Plates resist this shrinkage and may induce tensile stresses perpendicular to grain which may lead in return to splitting.

Cross Laminated Timber – New technology in timber engineering wood

Cross Laminated Timber – CLT, a modern concept to build with wood

The cross laminated timber as a new wood technology – may soon open up the construction sector to wood building. Wood is an excellent structural material because it is strong, lightweight, easy to work with, inexpensive and environmentally friendly Schickhofer 2011-2). The wood-framed construction, where dimension lumber in LWF in Poland (45x150 mm for studs and 60x222mm for joists and rafters, etc), are used to create the building's structure in small residential houses in many countries. This use in larger buildings above 3 stories is limited by building codes for structural and fire-resistance reasons. Cross laminated timber (CLT) refers to large panels that are created by laminating dimensional lumber. The panels can be very large – 15 m long, 3,00 m high and 0,30 m thick or larger – depending on the structure requirements. Because they are very thick, they have the excellent fire properties of big section timber elements. For example, for a CLT building in Britain, a four-person crew was able to assemble an entire floor of the nine-storey building in three days. CLT is now being manufactured and used in Europe, USA and Canada. Building with wood is good because it allows us to use an affordable and renewable material for one of out most important needs. CLT may new allow to build even more things with wood.

Cross-Laminated Timber Panels (Schickhofer 2011-1)

Cross-Laminated Timer Panels are formed using boards from 25mm thick x 120 – 170mm wide. laid and glued using formaldehyde-free, glue in a vacuum press in alternate layers, at 90 degrees to each other, creating panels that are from 3 to 11 layers thick. Quality control is optimized with the pre-fabrication of the structural panels in an atmospherically controlled facility using computer controlled cutting equipment. The primary benefits of the CLT system are the components' superior performance characteristics and the speed of the building process. When compared to traditional building materials and

technology, the CLT system has a number of significant advantages (Finch et al. 2011), (Karacabeyli, Desjardins 2011), (Mohammad 2011), (Pirvu et al 2011), (Schickhofer 2011-1), (Sorensen et al 2005), (Zurkov 1957), (EN 1992), including:

- Thermal efficiency: CLT buildings can double the energy efficiency of conventional buildings. The 'thermal mass' characteristics of the CLT building system allows to retain with less energy the ambient temperature of the internal environment of any building, ensuring minimum expenditures of heating and cooling costs.
- Acoustic protection: The mass of the wood in the CLT panels and specialized wood fiber insulation materials combine to achieve increased acoustic protection compared with other systems.
- Seismic strength: Buildings with similar components have been shown to exhibit superior performance to conventional buildings under earthquake hazards.
- Structurally better behavior under fire performance: CLT materials are highly fire-resistant and maintain extraordinary structural integrity under fire attack. Low carbon footprint: CLT materials are exceptionally 'green' when compared to competitively performing structural systems in consideration of the embodied energy in the building materials, the high energy efficiency of the CLT thermal envelope, and what will evolve into a carbon-neutral manufacturing process.
- Life cycle and future value: The long life time of CLT components ensures that the future value of any structure remains high; buildings are easily altered and remodeled and are also fully recyclable once they reach the end of their useful life.
- Flexibility of design: Cross-laminated timber panels have a high load bearing capacity and required serviceability limit state considering deflection and modulus of elasticity, providing designers with beautiful structural element for creating exciting new building designs.
- Speed and predictability of construction, where CLT structural systems is arrived on-site ready to assemble, saving time and giving an accurate building process. The raw materials for the CLT system are sourced exclusively from small and medium diameter timber thinned from the forest, as well as fire and insect killed salvage timber. This responsible cultivation practice maintains and even enhances the long-term productivity and health of the forest.
- Superior use of low-grade timber resources: CLT components can be manufactured from low-grade timber resources that otherwise would likely be converted to or consumed as fuel. Using this lumber as the primary raw material for its products is the most environmentally-friendly way to use this resource, which needs to be harvested in order to maintain the health and vitality of the source forests.

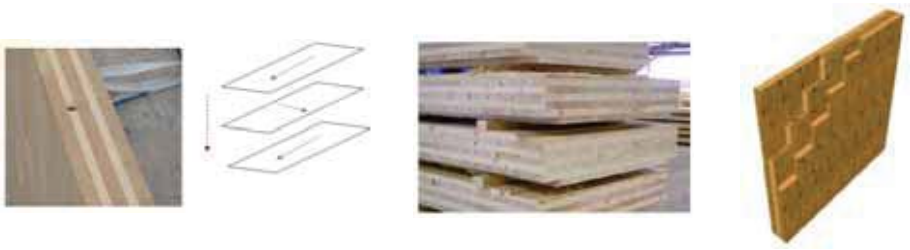


Fig.4. CLT panel formed of n-number of boards

CLT characteristics

There are the main factors affecting creep of wood (Pirvu et al. 2011):

- magnitude, type and duration of continuing application of load or a series of periods of the same type of load application. Creep rupture is attributed to the load duration effect,
- moisture content (service conditions)
- type of material (grain orientation, etc), hence the same conditions like in EN 1995-1-1 (EN 1992).

Canadian Standard on timber structure indicate the load duration factors in the function of duration of load like in the Table 1 , while the strength modification factors and the deformation modification factors are given in Table 2.

Table 1. Load duration factor K_D, according to CSA O86-09

Duration of load	K_D
Short term	1,15
Standard term	1,00
Long term	0,65

Table 2. Strength modification factor, according to EN 1995-1-1 (Zurkov 1957)

Load Duration Class	SC 1	SC 2	SC 3
k_{mod} for GLULAM/PLYWOOD			
Permanent	0,60	0,60	0,50
Long term	0,70	0,70	0,55
Medium term	0,80	0,80	0,65
Short term	0,90	0,90	0,70
Instantaneous	1,10	1,10	0,90

For CLT under 1 year constant load and 9%/25% ultimate load and SC1/SC2; 30-40% higher creep of CLT compared to glulam.
CLT behave more like plywood than like glulam.

Table 3. Deformation Modification Factor, Table 3.2, EN 1995-1-1 (EN 1992)

k_{def}	SC 1	SC 2	SC 3
LUMBER (EN 14081-1)	0,60	0,80	2,00
GLULAM (EN 14080)	0,60	0,80	2,00
PLYWOOD (EN 636)	0,80	1,00	2,50

Larger creep of CLT versus glulam is resulted from significant deformations of the cross plies in shear perpendicular to grain as it is presented in figure 5



Fig.5. Deformation due to rolling shear and higher creep in result.

For CLT under 1 year constant load and 9%/25% ultimate load and SC1/SC2 ; 30-40% higher creep of CLT compared to glulam.

Table 4 presents deformation modification facto for CLT.

Table 4. Factor k_{def} for CLT

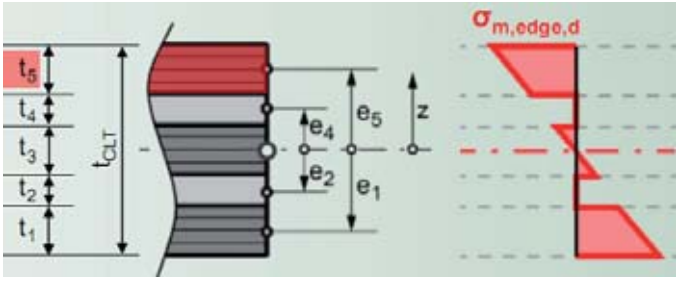
Proposed Deformation Modification Factor, k_{def}	SC 1	SC 2
CLT (less than 7-layer)	0,90	1,10
CLT (more than 9-layer)	0,80	1,00

CLT behave more like plywood than like glulam. Serviceabilty Limit State – deflection due to total load using 0,75 G_{90} with elastic deflection less than L/180 (according to CSA 086-09), and permanent deformation due to long term load using 0,5 G_{90} is not exceeding L/360 (Pirvu et al 2011).

CLT does not change basic wood characteristics and it does not change basic durability principles (Zurkov 1957) in case of wood kept dry wherever possible, minimizing wetting during transportation and construction, preventing wetting in service and allowing drying in case wetting occurs.

Stiffness characteristics of CLT (Schickhofer 2011-1)

BENDING



Calculation of the design value for E_{dg}-bending-stress $\sigma_{m,edge,d}$

$$\sigma_{m,l=5,edge,d} = \frac{M_{\max,d}}{K_{CLT}} \cdot \frac{t_{CLT}}{2} \cdot E_{l=5}$$

Bending stiffness of a layered cross section area

$$K_{CLT} = \sum_{i=1}^{n} \left(J_i \cdot E_i\right) + \sum_{i=1}^{n} \left(A_i \cdot e_i^2 \cdot E_i\right)$$

Calculation of the design value for bending strength $f_{m,clt,d}$
according to the load-bearing-model for CLT (TU Graz)

$$f_{m,clt,k} = a_{clt} \cdot f_{t,0,l,k}{}^{0,8} \Rightarrow f_{m,clt,d} = \frac{k_{\mathrm{mod}} \cdot f_{m,clt,k}}{\gamma_M}$$

with:
$f_{t,0,l,k}$ - characteristic tension strength of boards (raw material)
a_{clt} - pre-factor to take into consideration

- the coefficient of variation (COV) of the raw material
- the laminating effect
- the system effect
- the size effect
- the structure | assembling effect

load bearing model for CLT in bending according to technical approvals:

- ETA-09/xxx

with:

$$f_{m,clt,k} = \text{minimum}\begin{cases} a_{clt} \cdot f_{t,0,k}{}^{0,8} \\ 1{,}2 \cdot f_{m,k} \end{cases}$$

$f_{m,k}$ - characteristic bending strength acc. to EN 338
$f_{t,0,k}$ - characteristic tension strength acc. to EN 338
$a_{clt} = 3{,}5$ - for visually graded timber

- DIBt Z-9.1-xxx

$f_{m,clt,k} = k_l \cdot f_{m,glt,k}$ → reference depth $d_{ref,cit}$ not defined

need for research suggestion: $d_{ref,cit} = 150\,mm$

with:

$f_{m,glt,k}$ - characteristic bending strength for GLT $d_{ref,glt} = 600mm$

k_l - pre-factor to take in consideration the system effects $(k_l = 1{,}1\ if\ n \geq 4)$

Load bearing models for CLT in bending – a comparison:

example | strength-class C24 according to EN 338 or GL24h acc. to DIN 1052

- Load bearing model in bending
- $f_{m,clt,k} = a_{clt} \cdot f_{t,0,l,k}^{\ 0,8} = 3{,}5 \cdot 14{,}0^{0,8} = 28{,}9\ N/mm^2$
- ETA-09/xxx

$$f_{m,clt,k} = \min\begin{cases} a_{clt} \cdot f_{t,0,l,k}^{\ 0,8} = 3{,}5 \cdot 14{,}0^{0,8} = 28{,}9\ N/mm^2 \\ 1{,}2 \cdot f_{m,k} = 1{,}1 \cdot 24{,}0 = 28{,}8\ N/mm^2 \end{cases}$$

- DIBt Z-9.1.-xxx

$f_{m,clt,k} = k_l \cdot f_{m,glt,k} = 1{,}1 \cdot 24{,}0 = 26{,}4\ N/mm^2$

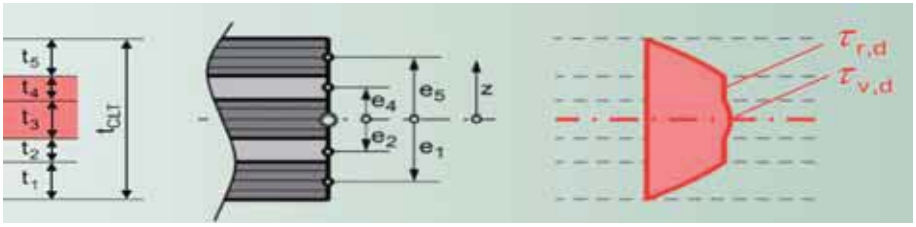
Note: system factor k_l conservative | no depth correction, $d_{ref,cit}$ not defined

$f_{m,clt,d=150,k} = k_h \cdot k_l \cdot f_{m,glt,k} = 1{,}1 \cdot 1{,}1 \cdot 24{,}0 = 29{,}0\ N/mm^2$

design

$\frac{\sigma_{m,edge,d}}{f_{m,clt,d}} \leq 1{,}0$ normally very low utilization ratio → seldom relevant

SHEAR | longitudinal | transverse (rolling shear)
calculation of the design value for shear stress



$$\tau(z_0)_d = \frac{V_{z,d} \cdot \int_{A_0} E(z) \cdot z \cdot dA}{K_{clt} \cdot b(z_0)}$$

→ $\tau_{v,d}$ (longitudinal) und $\tau_{r,d}$ (transverse)

Calculation of the design values of shear strength $f_{v,clt,d}$ and rolling shear strength $f_{r,clt,d}$

$f_{v,clt,k} = 3{,}0\,N/mm^2$, based on $f_{v,k}$ of GLT (approximate)

Considering the system effect, a 25% higher value for $f_{r,clt,k}$ compared to GLT is proposed (e.g. "BSP Handbuch" | TU Graz).

$f_{r,clt,k} = 1{,}25\,N/mm^2$, based on 'BSP handbuch' | TU Graz, design:

$\frac{\tau_{v,d}}{f_{v,clt,d}} \le 1{,}0$ $\frac{\tau_{r,d}}{f_{r,clt,d}} \le 1{,}0$ Both verifications normally result in a low utilization level.

Important role in CLT construction play connections. They maintain structural integrity, provide ductility for lateral load like wind and seismic, affect the serviceabilty limit state, they may also affect the fire resistance, facilitate a quick assembly of structure and interior and exterior finishes (Mohammad 2011).

Lateral performance of CLT wall panels ia governed by connections as it is indicated in figure

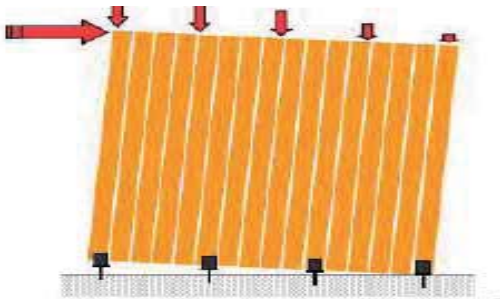


Fig.6. Lateral behavior of wall panel connected to the bottom structure.

Connections in CLT structures

Except traditional fasteners used in timber construction some special fasteners are used in TLC construction. There are self-tapping screws and dowels, glued in roads, bearing type systems and metal hooks. Diameters from 4 to 12 mm, length up to 600mm and they do not require predrilling like in traditional lag screws.

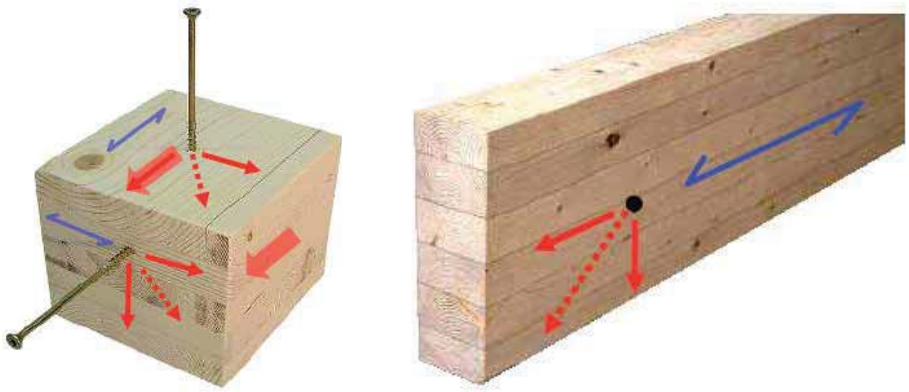


Fig. 7. Different way of loading in case of CLT, while in glulam all laminates are aligned and loaded in similar way (Orlowicz 1989-1).

Except this gaps in unglued cross laminates and artificially sawn grooves to relieve drying stresses in CLT are influencing load bearing capacity of connection. Despite this CLT has a more favorable ability to resist splitting due to X-lamination.

Nails & Screws – Generalized Approach

Perpendicular to plane

$$f_{h,k} = 0{,}112 \cdot d^{-0{,}5} \rho_k^{1{,}05} \; (N/mm^2)$$

In case of bolts and dowels formulae are described in the form as given below:

Bolts & Dowels

Perpendicular to plane

$$f_{h,k} = \frac{0{,}031 \cdot (1 - 0{,}015d) \cdot \rho_k^{1{,}16}}{1{,}1 \cdot \sin^2 \alpha + \cos^2 \alpha} \; (N/mm^2)$$

Panel-to panel connections in CLT panel construction is presented in figure and typical connections details:

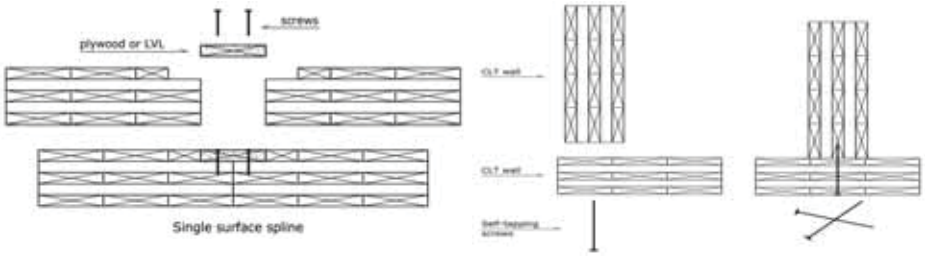


Fig. 8. Innovative connection systems [14]

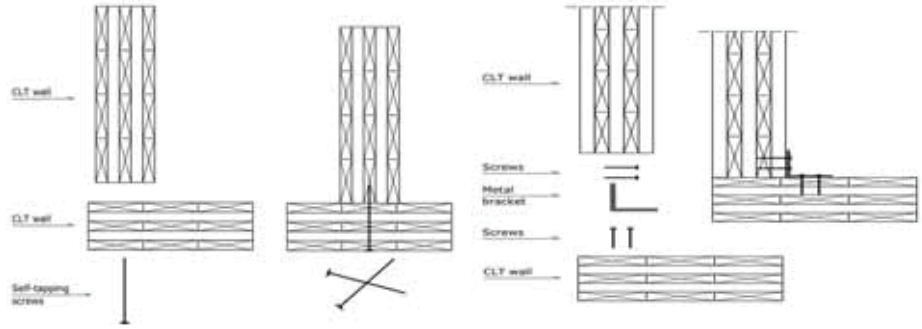
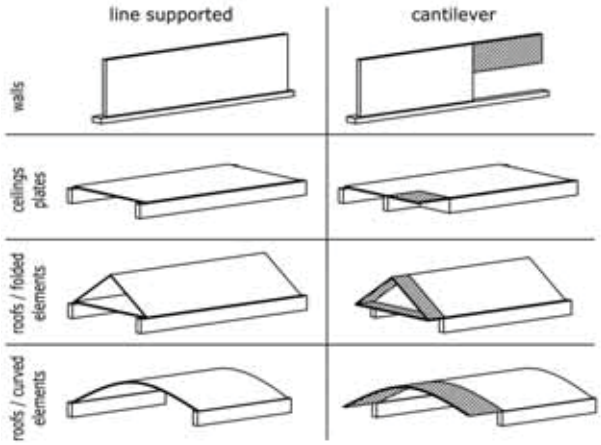


Fig. 9. Wall to wall connections [14].

Different types of elements
Use of CLT as 2D Elements



The diagram presents different static schemes of the supported along the wall and cantilever elements of CLT structure.

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