Properties of CLT-Panels Exposed to Compression Perpendicular to their Plane

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Mechanical properties of Cross Laminated Timber elements (CLT elements) compressed orthogonally to their plane are significantly better than those of comparable glulam. The reason for this can be found in the different lay-up of the CLT. Whereas glulam features only unidirectional layers (lamellas), CLT elements are built-up with layers orthogonal to each other. In this way adjacent layers of CLT elements support each other and act as an alternating "reinforcement", which leads to better mechanical properties than for timber or glulam.

This paper will present results for the stiffness and strength of cubic CLT specimens tested in accordance with EN 408 . The results for the mean value of the modulus perpendicular to plane $E_{c,90,clt,mean}=450$ *N/mm² and for the characteristic strength values perpendicular to plane* $f_{c,90,clt,k}=2.85$ *N/mm² are about 30% higher than those of comparable glulam specimens.*

In practice CLT elements are carried by linear or punctual supports (e. g. columns). For the design and verification $k_{c,90}-$*values are required and therefore tests for different loading situations ("central" - "longitudinal edge" - "crosswise edge" - "vertex") were carried out. Based on a characteristic strength values perpendicular to plane of* $f_{c,90,clt,k}=2.85$ *N/mm² and the loading situation* $k_{c,90,clt}-$*values (in accord. to EN 1995-1-1) between 1.4 and 1.9 can be proposed.*

1 Introduction and motivation

The use of Cross Laminated Timber (CLT) and the associated building system has become established as a new European solid timber construction technique. Within timber based building systems CLT is in competition with e. g. lightweight timber frame building systems. Naturally CLT also competes with different materials, e. g. building systems based on bricks and concrete. CLT plates are excellently applicable for single or multi-family houses as slabs acting uniaxially. In particular cases, which are illustrated in Figure 1, ceiling elements are subjected to biaxial load bearing behaviour due to the partially punctual support of the CLT plate.

Seen from an engineering point of view, this two-axial load bearing behaviour has to be verified according to the common plate theories derived by Kirchhof for plates without shear flexibility and by Reissner-Mindlin for general plates if shear effects are to be included. CLT is a strongly orthotropic structure in comparison to e. g. a steel plate and therefore the characteristic strength values and stiffness values are significantly lower in comparison to the values in the plane. This explains why especially the verification of punctual or line-shaped load introduction has such a high significance for CLT-plates.

This question is focused on in this paper and a proposal will be made for the verification of punctual load introduction by single columns perpendicular to the plane.

Figure 1: Solid timber building system with CLT, partially supported with columns

2 glulam: state of the art

2.1 Characteristic strength values perpendicular to grain for glulam

Quite a lot of research on the strength of glulam perpendicular to grain has been carried out which suggests that, it is more or less constant for all grading classes [1,4,8]. For a convenient comparison the strength values of international research of the last decade have been collected in Table 1.

Table 1: mechanical properties of glulam: compression perpendicular to grain ($f_{c,90,g,k}$)

Author	Series	Nr. of speci-men [-]	Gauge length [mm]	Density ρ_{12} [kg/m³]			MOE $E_{c,90}$ [N/mm²]			Strength $f_{c,90}$ [N/mm²]		
				$\rho_{12,mean}$	COV	$\rho_{12,k}$	$E_{c,90,g,mean}$	COV	$E_{c,90,g,k}$	$f_{c,90,g,mean}$	COV	$f_{c,90,g,k}$
Hoffmeyer, P.; et. al., 1999 [4]	-	120	200	466	4,8	433	274	13	215*	2,87	9,3	2,44‡‡
Augustin, et al., 2006 [1]	I/K1	19	200	490	5,02	449	299	19,86	201	3,10	22,10	1,99**
	I/K2	22	200	439	4,99	403	301	12,02	241	3,01	17,58	2,13**
	I/K3	21	200	418	11,98	335	320	22,91	200	3,12	18,01	2,18**
	II/1/MS10	41	200	417	7,71	364	265	21,24	172	3,35	19,62	2,33**
	II/1/ MS13	40	200	447	6,04	402	292	15,64	217	3,43	21,05	2,33**
	II/1/ MS17	41	200	493	6,04	444	318	16,81	230	3,16	17,58	2,30**
	All (weighted)	-	200	451	7,0	400	299	18,0	210	3,20	19,3	2,21**

Note:
* not given in the paper; calculated for a normal distribution
** characteristic value in accordance to EN 14358
‡‡ 5 % quantile value

According to the values given in Table 1, a characteristic strength value $f_{c,90,g,k}$ of 2.25 N/mm² can be proposed for glulam as a weighted mean value over all series.

2.2 EN 1995-1-1:2009 and EN 1994:1999

In EN 1995-1-1 [12] the verification of compression perpendicular to grain has to fulfill the following condition:

$$\sigma_{c,90,d} \leq k_{c,90} \cdot f_{c,90,d}$$

with:

$\sigma_{c,90,d}$ design stress perpendicular to grain
$f_{c,90,d}$ design strength perpendicular to grain
$k_{c,90}$ factor, taking into account partial compression situation

with the following definition of relevant stress perpendicular to grain:

$$\sigma_{c,90,d} = \frac{F_{c,90,d}}{A_{ef}}$$

with:

$F_{c,90,d}$ applied design load perpendicular to grain
A_{ef} associated effective area

This effective area is the contact area between the two parts, enlarged by maximum of 30 mm at each side in the grain direction. Additional rules, which can limit this increase of 30 mm, are given in detail in EN 1995-1-1 [12].

Values for the $k_{c,90}$ parameter are given in EN 1995-1-1 for glulam with

- $k_{c,90}$=1.50 for continuous support like swells and
- $k_{c,90}$=1.75 for single support like columns under beams

if specific geometric conditions are fulfilled.

For the resistance, the appropriate strength perpendicular to grain is found in EN 1194:1999 [15], where the following formula can be found:

$$f_{c,90,g,k} = 0.7 \cdot f_{t,0,l,k}^{0.5}$$

with:

$f_{c,90,g,k}$ characteristic strength perpendicular to grain for glulam (index '*g*')

$f_{t,0,l,k}$ characteristic tension strength of single lamella (index '*l*')

This formula leads to a characteristic strength value of $f_{c,90,g,k}$=2.70 N/mm², based on a tensile strength of $f_{t,0,l,k}$=14.5 N/mm² for widely used grading class GL24h. Increasing strength values of the boards lead to higher $f_{c,90,g,k}$ values of the glulam. The second factor, the so-called $k_{c,90}$ value, is given as a constant value − either 1.50 for continuous support or 1.75 for discrete support. Additional rules concerning some minimal length values are given in detail in EN 1995-1-1.

2.3 prEN 14080:2011

In this European standard [14], which is still a working document, a constant value of 2.5 N/mm² can be found for homogeneous and combined glulam.

2.4 Summary

In table 2 a summary of $f_{c,90,g,k}$ values is given for good comparison.

Table 2: Summary of $f_{c,90,g,k}$ strength values

	$f_{c,90,g,k}$	%	remark
research	2.25	*100*	based on [1, 4, 8]
EN 1194:1999 [15]	2.7	*120*	for glulam GL24h
prEN 14080:2011[14]	2.5	*111*	for all GLT strength classes

3 CLT perpendicular to plane – current research at TU Graz

3.1 Characteristic strength values for CLT

The basic strength value $f_{c,90,clt,k}$ has to be investigated similarly to glulam. Rules for the geometry of glulam test specimens are specified in EN 408 [13]. EN 408 demands cubes with a height of h_{ref}=200 mm and a minimum length of 100 mm in the fibre direction. The compressed area of the test specimens should be 25,000 mm², which leads to a size length of 160·160 mm². The tests conducted were analyzed according to EN 408 (limitation of remaining plastic strains perpendicular to grain to 1%, Fig. 2).

In order to achieve comparable results for CLT the same procedure and the same evaluation process was chosen for the CLT cubes. At Graz University of Technology two diploma thesis were carried out on this topic. The first one

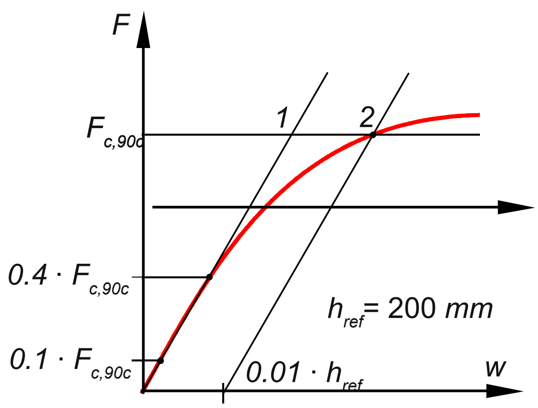

Figure 2: Evaluation of strength perp. to grain according to EN 408 [13]

was completed by Y. Halili [3] and the second one by C. Salzmann [9]. The results of these diploma thesis tie in well with results by E. Serrano et al. [1, 10].

Y. Halili investigated CLT produced under laboratory conditions. Therefore he was able to investigate effects due to following selected parameters: :

- Type of board (edge grained, flat grained boards) “Series I“
- Number of layers (3, 5, 7, 9 and 20 layers) “Series II“.
- Ratio of the thicknesses of adjacent layers. The number of layers investigated was 5 and 7. This ratio is given by the quotient of d_q/d_l “Series III“.

In contrast to this work Salzmann investigated 5-layered CLT test specimens with overall heights of 150, 161, 165 and 197 mm, which were produced by one single manufacturer. The type of board can only be classified as random as industrial CLT elements are predominantly edge grained but sometimes also flat grained and intermediate grained.

Series “I”

The parameters investigated in this series are the location of the boards in the original stem. Three different types of boards are focused on: flat-sawn timber, boards close to the pith and heartwood boards. These different boards are illustrated in Figure 3.

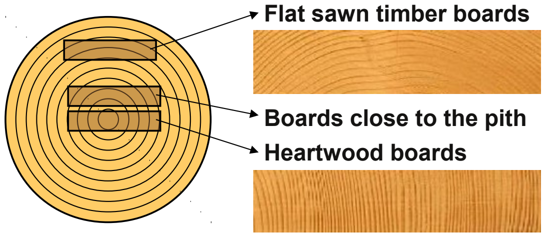

Figure 3: Different kinds of boards, investigated in series “I“[3]

Series “II”

The parameter investigated here is the number of layers. The numbers examined were 3, 5, 7, 9 and 20 (see Figure 4).

Series “III”

The parameter investigated here is the relative thickness of adjacent layers. This thickness relation is determined by the ratio of d_q to d_l. The values investigated for this parameter are d_q/d_l =1.0, d_q/d_l =2/3 and d_q/d_l =1/3. These tests were carried out with 5- and 7-layered CLT cubes. A typical picture of a 5-layered CLT cube can be seen in Figure 5.

Figure 4: Pictures of some test specimens of series “II“[3]

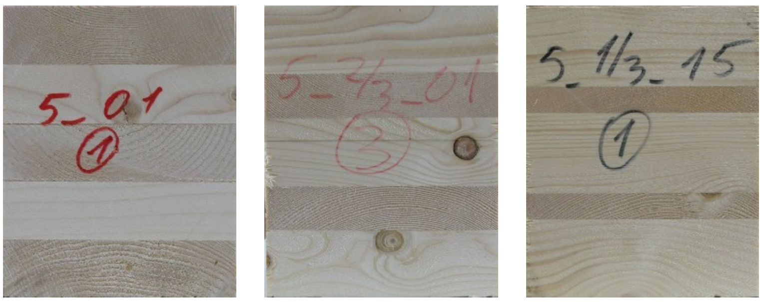

Figure 5: Pictures of some test specimens of series “III“[3]

Series based on cubes with origin in industrial production

In contrast to the series above the overall height of the CLT cubes tested in the diploma thesis of [9] varies between 150 mm, 161 mm, 165 mm and 197 mm. Some typical pictures of this industrially manufactured CLT cube series can be viewed in Figure 6.

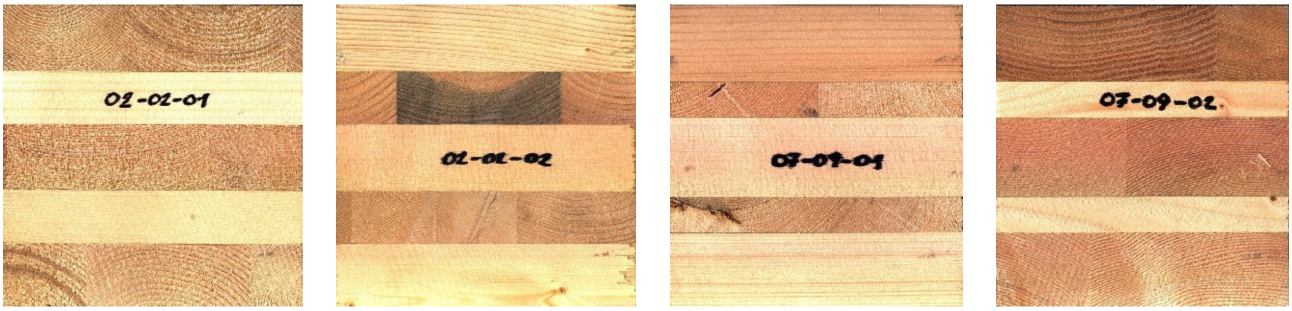

Figure 6: Pictures of some test specimens of industrially manufactured CLT [9]

Investigations of compression strength were also carried out by Al-douri, Hamodi [1] and Serrano and Enquist [10] in series “A”. They tested industrially produced CLT cubes with three layers, a thickness of 120 mm and a base area of 200·200 mm².

An overview of the results of all studies mentioned above [2, 8, 9] can be found in Table 3. Box plots for compression strength are shown in Figure 7. Left box plot shows cubes with same thickness, right box plot those with unequal layer thicknesses. Same box plots for mean stiffness can be seen in Figure 8. Based on these strength values a mean strength value $f_{c,90,clt,k}$ for CLT elements is suggested with 2.85 N/mm², which is an increase of about 27% based on $f_{c,90,g,k}$=2.25 N/mm² for glulam (see Chapter 2.1). A comparison of stiffness parameters perpendicular to plane for CLT and perpendicular to grain for glulam based on the values given in tables 1 and 3 shows a mean value of $E_{c,90,g,mean}$≈300 N/mm² for glulam (Table 1) and $E_{c,90,clt,mean}$≈450 N/mm² as a mean value over all for CLT (Table 3). The increase in stiffness amounts to 50%.

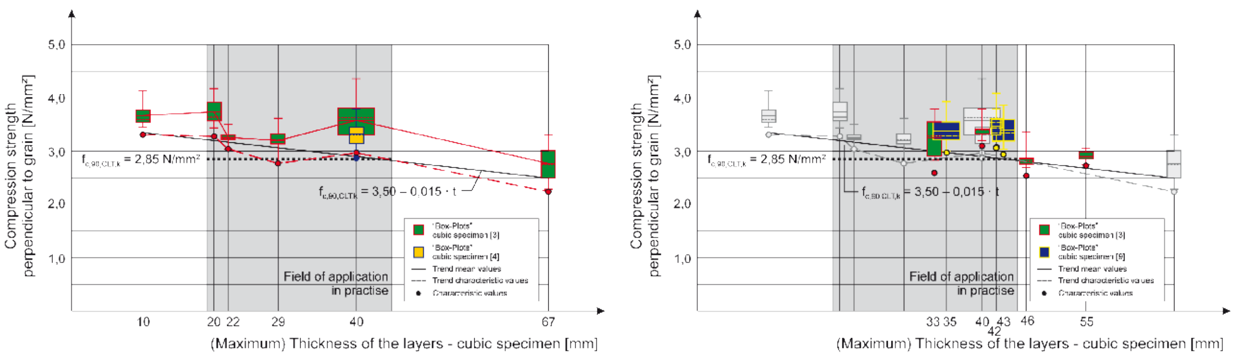

Figure 7: Box plots for compression strength perpendicular to plane

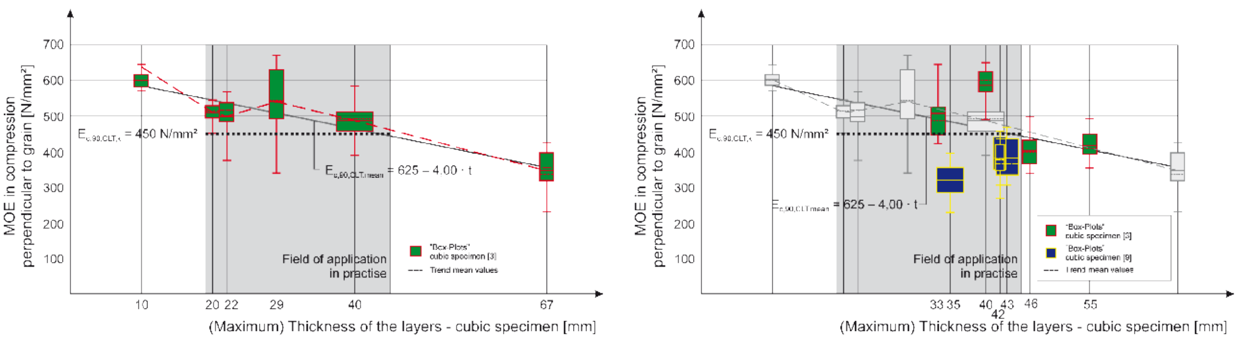

Figure 8: Box plots *for stiffness perpendicular to plane*

Table 3: mechanical properties of CLT: compression perpendicular to plane ($f_{c,90,clt,k}$)

Author	Series	Nr. of speci-men [-]	Gauge length [mm]	Density ρ_{12} [kg/m³]			MOE $E_{c,90,mean}$ [N/mm²]			Strength $f_{c,90}$ [N/mm²]		
				$\rho_{12,mean}$	COV	$\rho_{12,k}$	$E_{c,90,clt,mean}$	COV	$E_{c,90,clt,k}$	$f_{c,90,clt,mean}$	COV	$f_{c,90,clt,k}$ **
Halili Y., 2008 [3]	I_SW	16	200	449	5,1	411	532	7,5	466	3,22	3,5	3,00
	I_KN	16	200	427	4,1	398	482	4,7	444	3,36	4,1	3,10
	I_KW	16	200	419	3,0	399	426	10,5	352	4,28	4,7	3,89
	II_3	16	200	411	3,7	386	346	15,3	259	2,77	10,5	2,24
	II_5	41	200	421	4,3	391	487	9,6	410	3,58	9,9	2,97
	II_7	16	200	494	5,2	451	540	17,4	386	3,20	7,1	2,77
	II_9	16	200	452	3,1	429	499	10,8	411	3,26	3,6	3,04
	II_20	16	200	453	2,0	438	599	3,6	564	3,67	5,2	3,31
	III_5_1/3	16	200	452	2,3	435	402	10,5	332	2,86	6,2	2,54
	III_5_2/3	16	200	439	2,5	421	417	9,9	349	2,90	3,4	2,73
	III_7_1/3	16	200	436	4,9	401	507	15,5	377	3,25	11,1	2,59
	III_7_2/3	16	200	460	4,1	429	586	8,6	503	3,41	4,8	3,10
Salzmann C., 2010 [9]	"150"	15	150	462	4.9	425	440	13.0	346	3.52	7.8	3.01
	"161"	35	161	467	4.7	431	367	14.4	280	3.34	8.1	2.86
	"165"	27	165	442	3.8	414	435	13.5	338	3.33	10.0	2.69
	"197"	10	197	446	1.9	432	387	15.7	287	3.43	7.0	2.96
Al-douri, Hamodi [1] Serrano E., Enquist B., 2010 [10]	-	15*	120	430	2.9	410	-	-	-	3.33+	7.4	2.86+

Note:
** characteristic value in accordance to EN 14358
* specimen 200 x 200 mm
+ moisture content of specimen: mean u = 10,0 %

3.2 Load introduction in CLT plates – $k_{c,90,clt}$ factors

An increase factor $k_{c,90,clt}$, taking into account partly distributed loads similarly to glulam ($k_{c,90}$), has to be investigated for CLT. Four typical load arrangements (see Figure 9) can be detected to be most relevant for the actual problem [9]. The red area denotes the load introduction area with a size of 160·160 = 25600 mm².

Above test specimens with dimensions of 600·600 mm² basic area are made of the same CLT plates as the CLT cubes, which originate from the industrially manufactured CLT plates. Thickness h_{ref} of the particular CLT plates are 150 mm, 161 mm, 165 mm and 197 mm instead of h_{ref}=200 mm. Size of test specimens and test arrangement is illustrated in Figure 10.

Figure 11 shows some impressions of the deformed CLT plates under a condition, which is beyond the limits according to EN 408 [13].

Results of these tests are given in Table 4. The results include the 4 different CLT types, therefore results describe an average behaviour of CLT.

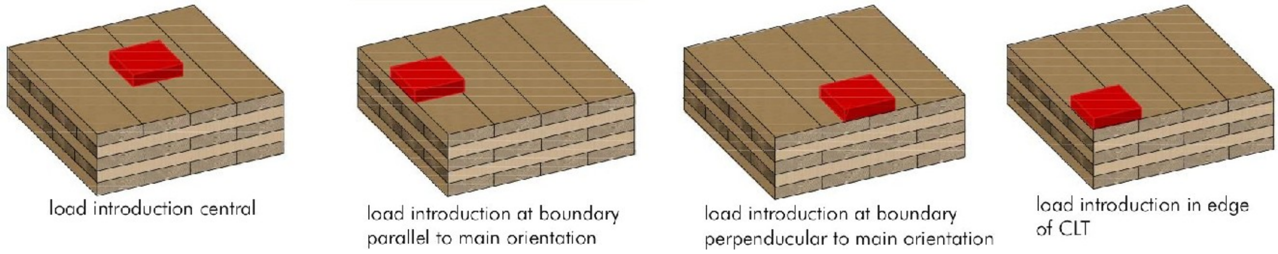

Figure 9: CLT with partly distributed loads – typical positions of loads for CLT plates [9]

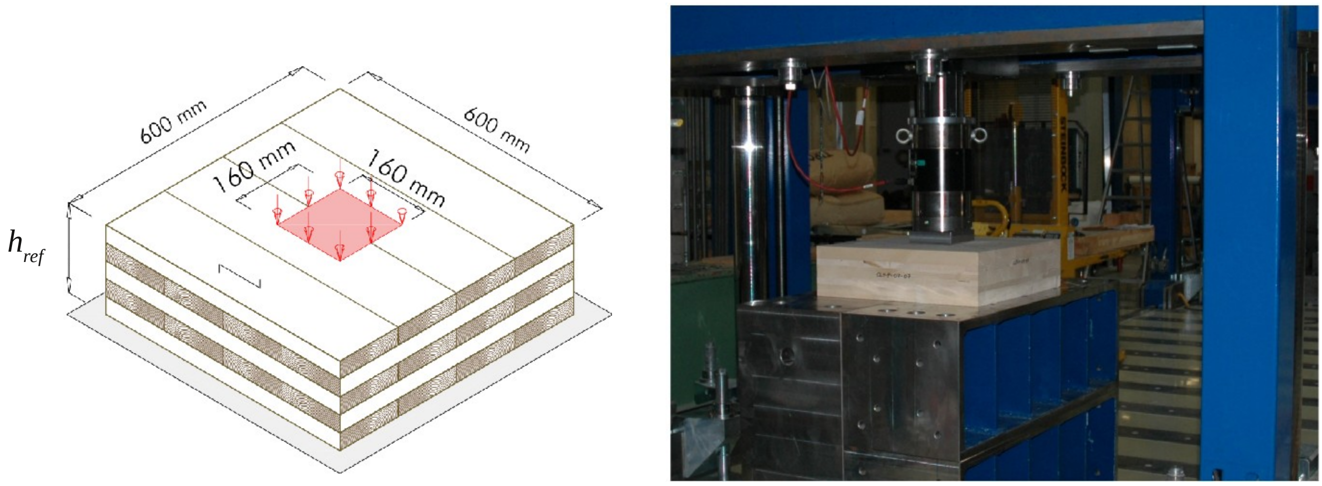

Figure 10: Test configuration and test arrangement for CLT with partly distributed loads [9]

Based on these test results, proper $k_{c,90,clt}$ factors can be derived based on a characteristic strength value $f_{c,90,clt,k}$ with 2.85 N/mm² ($k_{c,90,clt}$ see Table 5).

Remark: These $k_{c,90,\ clt}$ values do not make use of the additional enlargement in fibre direction of the load introduction area, as it is specified for glulam with a maximum value of 30 mm at each side. Characteristic load perpendicular to plane can be calculated now

$$F_{c,90,clt,k} = k_{c,90,clt} \cdot f_{c,90,clt,k} \cdot A$$

with:

$F_{c,90,clt,k}$	characteristic design load perpendicular to plane
$k_{c,90,clt}$	factor, according to Table 5
$f_{c,90,clt,k}$	characteristic strength value perp. to plane with $f_{c,90,clt,k}$=2.85 N/mm²
A	associated contact area, which transmits load into CLT

Figure 11: CLT plates with partly distributed loads – deformations [9]

Table 4: mechanical properties of CLT plates with partly distributed loads [3,9,10]

Author	Series	Nr. of speci-men [-]	Gauge length [mm]	Density ρ_{12} [kg/m³]			Apparent stiffness $K_{90,app}^{(+)}$ [N/mm²]			Strength $f_{c,90}$ [N/mm²]		
				$\rho_{12,mean}$	COV	$\rho_{12,k}$	Mean	COV	5 %	$f_{c,90,clt,mean}$	COV	$f_{c,90,clt,k}^{**}$
Halili Y., 2008 [3]	central	5	200	419	0,8	414	736	7,2	649	5,92	4,8	5,26
Salzmann C., 2010 [9]	central	3	150	488	0,9	480	632	9,2	536	6,37	7,6	5,02
		3	161	478	6,5	427	631	14,3	483	6,54	6,0	5,41
		5	165	454	1,0	446	649	16,3	475	5,72	11,1	4,33
		4	197	443	1,5	432	632	6,7	563	7,01	5,4	6,07
		15	***	463	2,2	445	636	11,9	512	6,36	7,9	5,15
	Longi-tudinal edge	3	150	488	0,9	480	572	12,7	453	5,08	16,2	2,94
		3	161	484	1,1	476	504	15,2	378	5,01	3,9	4,42
		5	165	448	2,9	426	555	17,2	398	5,50	11,3	4,14
		11	***	469	2,0	454	546	15,4	408	5,25	10,6	3,89
	Crosswise edge	3	150	488	0,9	480	578	7,1	510	4,97	4,1	4,37
		3	161	439	2,0	425	440	9,6	370	5,09	8,6	3,88
		5	165	442	2,6	423	493	13,0	388	5,47	11,4	4,05
		11	***	454	2,0	439	502	10,5	416	5,23	8,7	4,09
	vertex	3	150	465	5,7	421	435	14,9	328	4,45	12,8	2,99
		3	161	450	1,6	439	455	6,6	406	4,81	3,3	4,32
		5	165	438	1,9	425	514	4,8	473	5,03	10,6	3,83
		4	197	445	1,6	433	470	6,7	418	5,52	7,6	4,48
		15	***	448	2,5	429	475	7,7	416	5,00	8,8	3,93

Note:
* not given in the paper; calculated for a normal distribution
** characteristic value in accordance to EN 14358
*** all weighted
\+ apparent stiffness $K_{90,app}$ due to load spreading in CLT plate, for details see [9]

Table 5: Proposal for $k_{c,90,clt}$ values depending on $f_{c,90,clt,k}$ for the different load introductions

Load introduction	# of tests	$f_{c,90,clt,k}$ *[N/mm²]*	$k_{c,90,clt}$ *[−]*
central	15	2.85	1.8
longitudinal edge	10		1.5
crosswise edge	10		1.5
vertex	15		1.4

4 Numerical analysis

4.1 Stiffness calculation of CLT and glulam cubes

Due to a good correlation between strength perpendicular and stiffness [3] numerical results regarding stiffness comparison between glulam and CLT will be shown here on basis of a linear elastic orthotopic material behaviour. The increase in stiffness could be a good orientation for the increase in strength. Mechanical behaviour strongly depends on the poisson ratios of the material parameters. The two models (glulam-cube, CLT-cube) with a basic area of 25600 mm² consists of 5 boards in each case. Two different heights are investigated: one height is 150 mm with lamella thickness of 30 mm, the second height is 200 mm with lamella thickness of 40 mm. Material parameters are taken from F. H. Neuhaus [6] and summarized in Table 6 for moisture content of 12%. Numbering and sequence of axis in table 6 is 1 for radial, 2 for tangential and 3 for longitudinal. Poisson values (μ_{rt}, μ_{rl}, μ_{tl}) of Table 6 are below the main diagonal of the compliance material matrix in notation of Voigt. Material orientation of each board is modeled in a zylindrical coordinate system. Heartwood boards are located in the middle of a stem and therefore the location of board in stem is 0 cm (Table 7). Flat sawn timber boards are those with a high distance from the stem. In Table 7 boards with a maximum distance of 25 cm are shown. A fixed deformation of 2 mm is applied to glulam and CLT cubes. Impressions to this fixed deformation is given in Figure 13. The increase of stiffness of CLT cube versus glulam cube depending on the type of board (heartwood – flat sawn) is given in Table 7.

Table 6: elastic orthotropic material parameters [6]

E_r	E_t	E_l	μ_{rt}	μ_{rl}	μ_{tl}	G_{rt}	G_{rl}	G_{tl}
820	420	12000	0.602	0.042	0.027	42.4	620	740

Table 7: calculated increase of stiffness −glulam versus CLT cube

	height of cube h=200 *mm*			height of cube h=150 *mm*		
location of board in stem	$E_{90,g}$	$E_{90,clt}$	$\Delta=\frac{E_{90,clt}-E_{90,g}}{E_{90,g}}\cdot 100$	$E_{90,g}$	$E_{90,clt}$	$\Delta=\frac{E_{90,clt}-E_{90,g}}{E_{90,g}}\cdot 100$
0 [*cm*]	367	434	18%	382	448	17%
5 [*cm*]	351	535	52%	370	535	45%
10 [*cm*]	505	653	29%	539	658	22%
15 [*cm*]	612	738	21%	646	748	16%
20 [*cm*]	678	792	17%	709	805	14%
25 [*cm*]	721	826	15%	747	840	12%

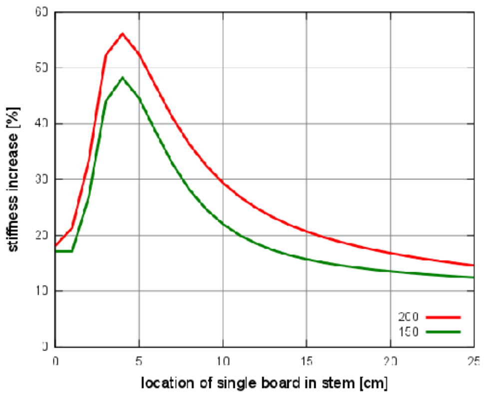

Figure 12: Difference of stiffness between glulam and CLT cube

Based on these simulations an increase in stiffness for ordinary CLT cubes in relation to glulam cubes can be expected to be approximately 30% as an averaged value (see Figure 12).

4.2 Calculation of load bearing capacity of CLT plates and timber swells

For comparison purpose a finite element simulation was carried out, taking into account the non-linear ductile material behaviour of timber under pressure perpendicular to grain. Material formulation is purely linear orthotropic elastic in all directions. An elastic-plastic material formulation is introduced additionally parallel to load direction, that means perpendicular to plane. The elastic-plastic behaviouris handled according to the algorithms in [11]. A brief overview of the governing equations is given here for uniaxial behaviour.

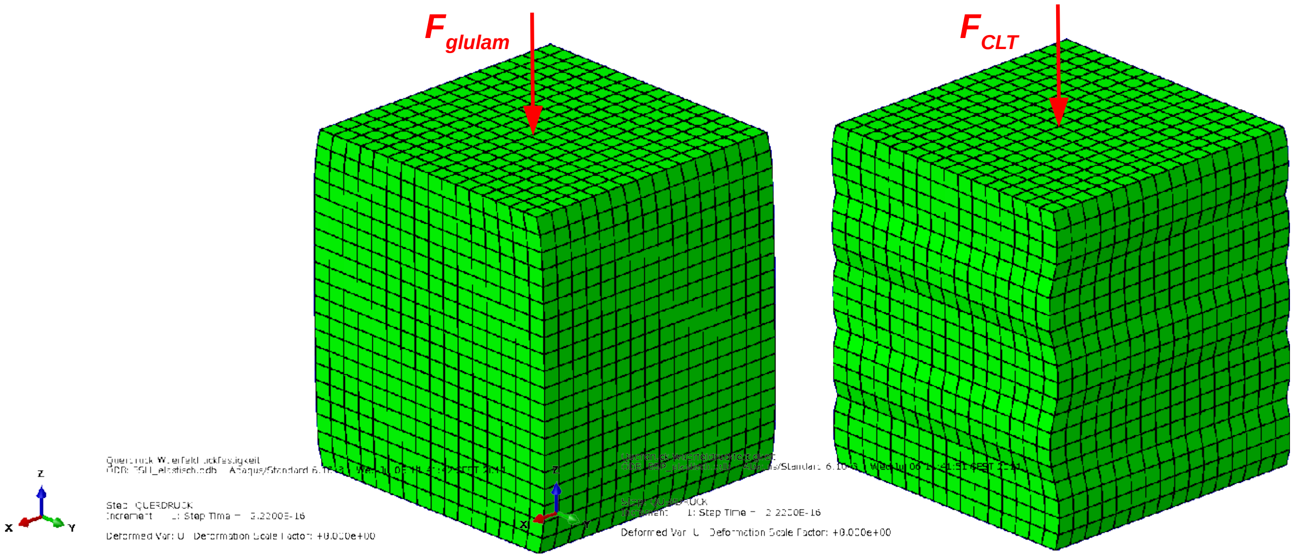

Figure 13: 200 mm high glulam cube (left) and CLT cube (right) under fixed deformation of 2 mm

Flow rule for simple one axial material behaviour is given by [11]

$$f(\sigma, q) = |\sigma| + q_{iso} - f_y = 0$$

with:

$f(\sigma,q)$	flow rule equation	
σ	stress component	[N/mm²]
q_{iso}	isotropic hardening stress	[N/mm²]
f_y	strength or yield strength	[N/mm²]

Material law for stress component is formulated with the elastic strains ε_{el}. A linear additive decomposition of the total stain (ε) in an elastic part (ε_{el}) and a plastic (ε_{pl}) part is assumed. The material equations for the stress component σ and the hardening component q are given in terms of rates. Rates are written in dotted notation $\dot{()} = d()/dt$ (derivations to t).

$$\varepsilon = \varepsilon_{el} + \varepsilon_{pl}$$
$$\dot{\sigma} = E \cdot (\dot{\varepsilon} - \dot{\varepsilon}_{pl})$$
$$\dot{q}_{iso} = -H \cdot \dot{\alpha}$$

with:

ε	total strain	[-]
ε_{el}	elastic part of the strain [-]	
ε_{pl}	plastic part of the strain [-]	
E	modulus of elasticity	[N/mm²]
H	linear hardening modulus	[N/mm²]
α	variable, taking into account internal damage (energy dissipation) due to plastic flow	[-]

Two evolution equations are needed additionally, in order to solve these unknowns (ε_{pl}, α, σ, q_{iso}). Associated flow rule leads to the two equations, formulated also in terms of rates.

$$\dot{\varepsilon}_{pl} = \lambda \cdot \frac{\partial f(\sigma, q_{iso})}{\partial \sigma} = \lambda \cdot \mathrm{sign}(\sigma) \quad \text{with derivation of} \quad \frac{\partial f(\sigma, q_{iso})}{\partial \sigma} = \mathrm{sign}(\sigma)$$

$$\alpha = \lambda \cdot \frac{\partial f(\sigma, q_{iso})}{\partial q} = \lambda \quad \text{with derivation of} \quad \frac{\partial f(\sigma, q_{iso})}{\partial q} = 1$$

with:

λ Lagrange Parameter, further unknown to be solved

Consequent extension to 3D linear elastic orthotropic has to be further accomplished under inclusion of elastic-plastic material behaviour in radial axis. Little linear hardening has been regarded here, because tests show good agreement with this assumption.

The integration algorithm of equations above is preferably the well known return-mapping algorithm for isotropic hardening, e.g. [11]. This linear orthotropic 3D elastic material model with elastic-plastic behaviour perpendicular to plane, a consistent elastic-plastic 3D material stiffness matrix and a local iterative implicit solution scheme is realized as a FORTRAN user subroutine for the general FE package ABAQUS. The chosen material parameter for the material are extracted from [9] and given in Table 8. Local orientation of the material was chosen, that the elastic-plastic behaviour appears in the radial direction, which is perpendicular to plane.

Table 8: material parameters for the user subroutine in ABAQUS

$E_{\|\|}$	E_T	E_R	μ_{tl}	μ_{rl}	μ_{rt}	G_{LT}	G_{LR}	G_{TR}
11600.0	300.0	300.0	0.02	0.02	0.40	650.0	650.0	65.0

An elastic-plastic behaviour is formulated in radial direction (E_R). The assumed yielding strength is 2.10 N/mm². Linear hardening is assumed, as the linearity of hardening is sufficient in the scope. Non linear hardening occurs later when higher compression strains have been developed. The linear hardening module H is assumed with a value of 3.0 N/mm². Using material parameters of Table 8, the elastic-plastic behaviour of the material in radial direction is shown in Figure 16. This approach realizes the main material behaviour directly in a mechanical model without using extension of the von Mises yield criterion to orthotropic materials (Hill's criteria). Failure due to shear and tension parallel to grain can be added in these models by cohesive planes, but these improved models are not presented in this paper.

Both timber swells (length=900 mm, width=160 mm, height=90/200/480 mm) and CLT plates (600 mm/600 mm/165 mm) under partial load introduction were investigated by the numeric model. In the following figure 14 some impressions of these timber swells in a deformed situation are given, whereas deformed CLT plates (only central and vertex loaded CLT plates) are shown in Figure 15.

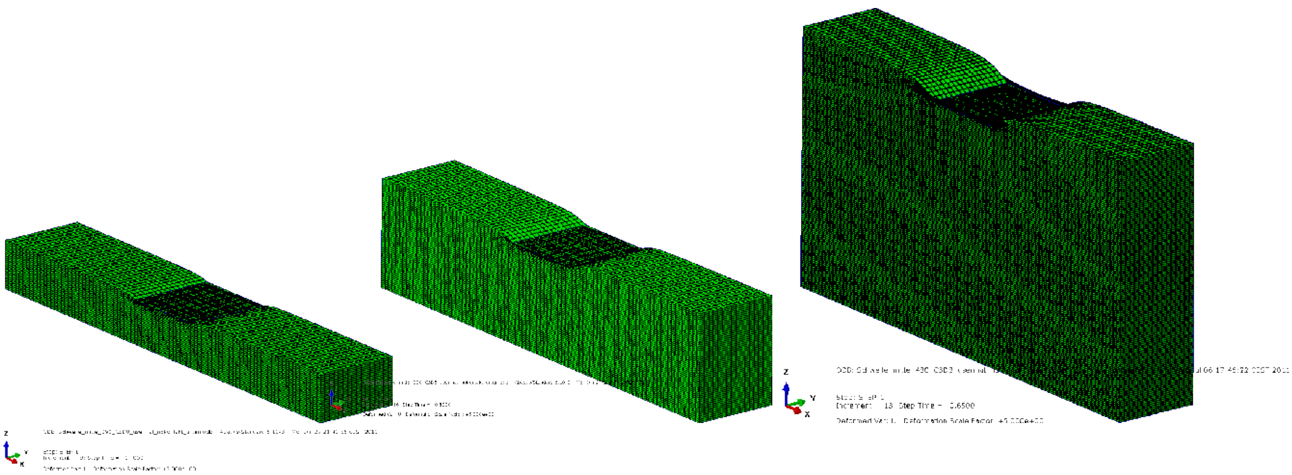

Figure 14: deformed timber swells (90/200/480 mm height)

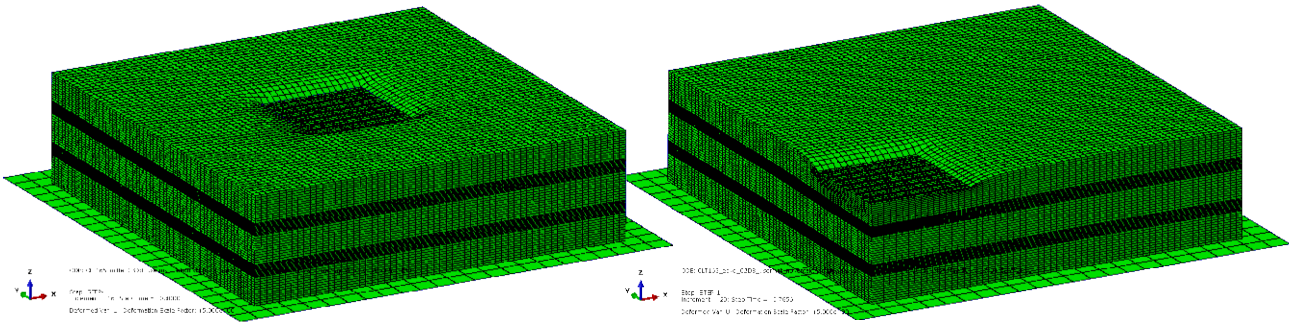

Figure 15: deformed CLT plates (height=165 mm, load position central/vertex)

Calculated load displacement curves are illustrated in Figure 17 for three swells (length=900 mm, width=160 mm, height=90/200/480 mm) and CLT-plates with four positions of loads (600 mm/600 mm/165 mm).

The following $k_{c,90}$ and $k_{c,90,\,clt}$ factors can be calculated, based on these load displacement curves, using the evaluation procedure according to EN 14358:2007. As the ultimate load perpendicular to plane is a product of the basic strength value $f_{c,90,k}$ and the associated $k_{c,90}$ factors, assumptions for the basic $f_{c,90,k}$ values have to be made. $f_{c,90,g,k}$ values for swells (glulam) are assumed with 2.25 N/mm², $f_{c,90,clt,k}$ values for CLT are assumed with 2.85 N/mm². Results of $k_{c,90}$ factors are summarized in Table 9.

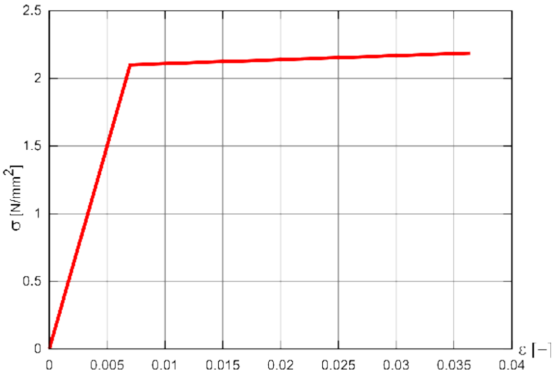

Figure 16: elastic-plastic behaviour in radial direction

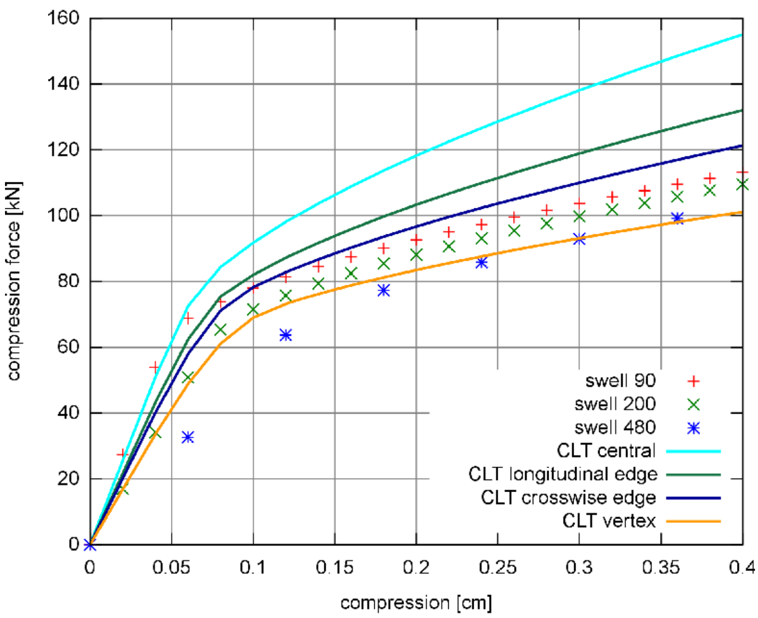

Figure 17: calculated load displacement curves for swells and CLT plates under punctual loads

By means of the numerical calculations, well known influence of height of structure on $k_{c,90,clt}$ factors can be studied. As the height for CLT differs only little, influence is expected to remain small. A comparison is given in Table 10, comparing CLT with height of 165 mm and 200 mm.

Table 9: $k_{c,90}$ and $k_{c,90,clt}$ factors, based on a numeric model for swells and CLT plates in comparison to experimental test results

	FEM simulations	empirical tests	
swells	$k_{c,90}$	$k_{c,90}$	source
swell height=90 *mm*	1.50	–	–
swell height=200 *mm*	1.77	1.9	Augustin et al. [1]
swell height=480 *mm*	2.32	2.5	
CLT plate	$k_{c,90,clt}$	$k_{c,90,clt}$ based on table 5	
load position “central”	1.83	1.8	Salzmann [9]
load position “longitudinal” edge”	1.58	1.5	
load position “crosswise edge”	1.47	1.5	
load position “vertex”	1.25	1.4	

Table 10: comparison of $k_{c,90,clt}$ factors for CLT with different height

	$k_{c,90,clt}$ (165)	$k_{c,90,clt}$ (200)
load position “central”	1.83	1.93
load position “longitudinal” edge”	1.58	1.66
load position “crosswise edge”	1.47	1.53
load position “vertex”	1.25	1.30

Influence of load introduction area is also studied by the FE-model. Two different load areas in comparison to the standard area with 160·160=25600 mm² are studied: a smaller one (50 % area reduction) is chosen with 113·113≈12800 mm² and a large one (50% increase) with 196·196≈38400 mm². Results of the FE study are given in Table 11 for a constant CLT height of 200 mm.

Table 11: comparison of $k_{c,90,clt}$ factors for CLT with variation of load introduction area

	relative area	$k_{c,90,clt}$ (h_{ref}=200 mm)
standard area 160·160 *mm²*	100%	1.93
enhanced area 196·196 *mm²*	150%	1.93·0.90
reduced area 113·113 *mm²*	50%	1.93·1.35

5 Discussion of results

5.1 Glulam

A proper compression strength perpendicular to grain, based on rules of EN 14358:2007, can be presented with a value of $f_{c,90,g,k}$=2.25 N/mm². This $f_{c,90,g,k}$ value can be considered as reliable, as a comparison and evaluation of a internal series [1] and another international series [4] shows in Chapter 2.1. A big difference can be observed to proposed values in actual codes with a value of $f_{c,90,g,k}$=2.7 N/mm² [15], which results in a remarkable difference of 20%. Especially partial load introduction is of particular interest in timber engineering and in such situation an additional factor, called as $k_{c,90}$, can be applied. Ultimate compression resistance perpendicular to grain is remarkable increased by this $k_{c,90}$ factor.

International discussion has been often controlled by the question, whether compression perpendicular to grain is a real ULS verification or is it only a SLS verification with loads at the ULS level. Discussion can be summarized also with the question whether compression strain perpendicular to grain leads to dangerous loss of strength or only to a reduction of serviceability.

Let us consider a continuous beam with two spans at the internal support, where a large hogging moment exists. Load introduction take place by resistance perpendicular to grain (see Figure 18). Two different heights of this glulam beam should be considered, one with 200 mm, the second with 480 mm height.

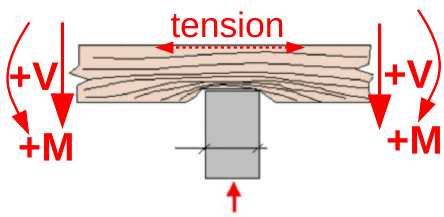

Figure 18: continuous beam with internal support

Based on FE investigations, relevant $k_{c,90}$ values for beams at internal support are marginally higher than comparable values for continuous support. Use of conventional $k_{c,90}$ factors for continuous support are therefore at the safe side.

T. A. C. M. van der Put [7] published reliable $k_{c,90}$ values, based on a stress equilibrium equations and the so called method of characteristics as mathematical solution technique for solution of differential equations. He published the simple formula

$$k_{c,90}=\sqrt{\frac{L}{s}}\leqslant 5 \text{ with } L=s+3\cdot H$$

with:

s length of load introduction

H height of swell

Limitations like small distance to end of swell (a) or second load near introduction (l_1) do not apply $k_{c,90}$ in this example [5]. A comparison for two heights of glulam beams (200 mm and 480 mm) are given in Table 12 and 13.

Table 12: comparison of compression strength of glulam beam (height=200 mm) at internal support

source of $k_{c,90}$	$k_{c,90}$	$f_{c,90,k}$	$f_{c,90,k}\cdot k_{c,90}$	Diff [%]
Augustin et al	1.90	2.25	4.28	[–]
FEM	1.77	2.25	3.98	-6.84%
van der Put	1.70	2.25	3.82	-10.76%

Table 13: comparison of compression strength of glulam beam (height=480 mm) at internal support

source of $k_{c,90}$	$k_{c,90}$	$f_{c,90,k}$	$f_{c,90,k}\cdot k_{c,90}$	Diff [%]
Augustin et al.	2.50	2.25	5.63	[–]
FEM	2.32	2.25	5.22	-7.20%
van der Put	2.35	2.25	5.28	-6.19%

Based on the characteristic compression strength perpendicular to grain, given in 2.1, differences of calculated strength for the partial load introduction in the glulam beam are in the range up to 10% (Table 12 and 13). It is noted in [5], that strains perpendicular to grain can be expected in the range of 10% for loads at ULS level, if a stress distribution of 1:1.5 is used. As $k_{c,90}$ factors in Table 12 and 13, calculated with formula of van der Put, agree well with those of Augustin et al., which are evaluated at 1% plastic compression strain limit, reason could be found in the lower characteristic strength $f_{c,90,k}$ of 2.25 N/mm².

EN 1995-1-1 delivers a $k_{c,90}$ value of $k_{c,90}$=1.75 for this situation. Together with the effective length of 2·30=60 *mm* and a characteristic strength of $f_{c,90,g,k}$=2.7 N/mm² a characteristic compression strength of $k_{c,90}\cdot f_{c,90,g,k}$=1.75·(220/160)·2.70=6.50 N/mm² can be calculated. A quick comparison shows, that load introduction in the small beam is overestimated by 52% for height 200 mm and 15.5% for 480 mm.

5.2 CLT

The situation for CLT is slightly different to glulam. A strong variation in height can not expected, CLT elements vary between 120 and 200 mm in standard case. A reliable compression strength perpendicular to plane can be presented with a value of $f_{c,90,clt,k}$=2.85 N/mm². Appendant $k_{c,90,clt}$ values are in the range of 1.3 up to 1.8, depending on the load introduction, as given in Chapter 3.1 and 4.2. A serious situation can occur in the internal domain at local support with columns, where hogging moments take place additionally. Here a $k_{c,90,clt}$ factor of 1.8 could mark a good choice, which prevents large deformations perpendicular to plane, which would leave to perpendicular overstraining due to the hogging moments in the plate. If a 30% overload over the characteristic strength in a CLT plate is assumed, a strain of about 3.12% (about 2.25% remain as plastic strain) can be calculated based on curve “CLT central” of Figure 17. This strain leads to a total deformation of about 5 mm for a CLT element with an overall height of 165 mm. Due to this reduction of cross section height, loss in bending height can be expected with about 6%, based on reduction of section modules.

Reinforcements in CLT plates for compression perpendicular to plane were not treated up to now. Several solutions exist and this topic could mark the next step of research at competence center for Timber Engineering and Wood Technology in Graz.

6 Summary

Characteristic strength values for CLT with $f_{c,90,clt,k}$=2.85 N/mm² has been proposed. Associated $k_{c,90,clt}$ values depend only marginally on geometric parameters like height (Table 10) and load introduction area (Table 11). Therefore a $k_{c,90,clt}$ of 1.9 for central loading can be proposed. Other load positions are summarized in Table 10. For simplification purpose a minimal $k_{c,90,clt}$ value of 1.4 for all non central load positions can be proposed. Further research work should be carried out on reliable functions for $k_{c,90,clt}$, taking into account influence of CLT height and load intoduction area.

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