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Lorenzo Franzoni, Arthur Lebée, Gilles Forêt, Florent Lyon. Advanced modelling for design helping of heterogeneous CLT panels in bending. International Network on Timber Engineering Research - INTER - Meeting 48, Sibenik - Croatia, Aug 2015, Sibenik, Croatia. hal-01233249

HAL Id: hal-01233249
https://hal.science/hal-01233249

Submitted on 24 Nov 2015

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Advanced modelling for design helping of heterogeneous CLT panels in bending

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Keywords: Cross Laminated Timber, bending, modelling, heterogeneities, bending tests, innovative floors

1 Introduction

Cross Laminated Timber panels are gaining importance in timber construction, due to their advantages coming from their crosswise lay-up. However the heterogeneities affecting their bending behaviour still require advanced tools for being taken into account.

In the first part of the present paper the “low” heterogeneities are mainly represented by gaps between narrow boards of each layer and CLT transverse shear weakness. The suggested equivalent-layer model at the layer scale combined with the 3D exact structure solution (Pagano, 1969 – 1970) and a failure criterion for wood (van der Put, 1982) provide a good comparison with a reference test (Hochreiner, 2013). Then, parameter studies are performed with the validated model in order to quantify shear effects and the influence of varying layers’ number and orientation.

The second part of this paper deals with stronger CLT heterogeneities, namely regularly spaced voids within the panel. The results of an experimental campaign are presented. The experimental behaviour is therefore compared with the behaviour predicted with the equivalent-layer model and design methods for CLT (Eurocode 5, 2004, Kreuzinger, 1999). The input mechanical properties are reduced by wood volume fractions. The results of this comparison shows the need of a more accurate modelling which is currently in development. The first results of such a new modelling procedure are presented as well.

2 Low heterogeneities

A previous study (Franzoni et al, 2015) identified the gaps between lateral boards of each layer and CLT transverse shear weakness as the main "low heterogeneities" affecting their bending behaviour. In the following, the modelling procedure and main results are briefly summarized.

2.1 Modelling

CLT heterogeneities are taken into account with a combined equivalent layer-based mechanical model at the layer scale (Fig. 1) and the exact 3D solution at the structure scale (Pagano, 1969 – 1970). The equivalent layer model takes into account the edge-gluing or not of lateral boards by means of simplified hypotheses on layer's mechanical behaviour (Tab. 1). A failure criterion for wood (van der Put, 1982) is implemented in order to include a failure analysis. The reference bending behaviour (Hochreiner, 2013) documents well the elastic and failure response of CLT, highlighting the edge-gluing detachment as a firs failure mode. The comparison is made in terms of panel's global stiffness and failure stages within the apparent elastic regime.

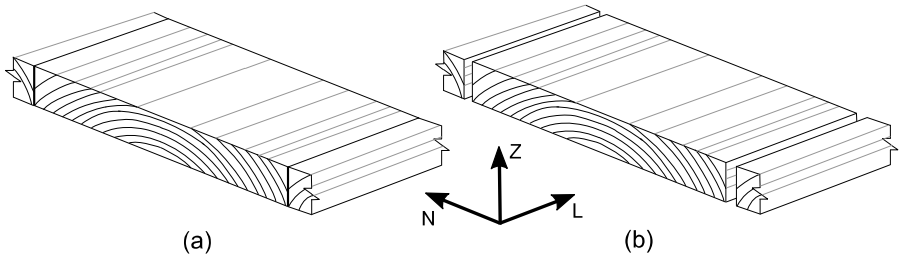


Figure 1 Schematic representation of continuous (a) and discontinuous (b) equivalent layer with the layer's reference frame

Table1 Elastic and strength properties of continuous and discontinuous equivalent layers [Mpa]

Elasticity (Keunecke et al, 2008)	E_L	E_N	E_Z	G_{LZ}	G_{LN}	G_{ZN}	ν_{LZ}	ν_{LN}	ν_{ZN}
Continuous	12800	511	511	602	602	53	0.41	0.41	0.21
Discontinuous	12800	0.0	511	602	602	53	0.41	0.0	0.0

Failure (Dahl, 2009)	$f_{L,t}$	$f_{L,c}$	$f_{N,t}$	$f_{N,c}$	$f_{Z,t}$	$f_{Z,c}$	f_{LZ}	f_{LN}	f_{ZN}
Continuous	63.4	28.9	2.8	3.6	2.8	3.6	4.8	4.8	2.0
Discontinuous	63.4	28.9	-	-	2.8	3.6	4.8	4.8	2.0

2.2 Results

Comparison / edge-gluing. Each equivalent-layer model turns out to fit well the reference behaviour within the corresponding edge-gluing regime. It appears that edge-glued layers increase CLT panel's stiffness of about 8% but introduces also an additional failure mode. Indeed, the edge-gluing detachment is one of the first failure modes, and therefore the discontinuous model gives a better prediction of

global load-carrying capacity in terms of failure modes (see Franzoni et al, 2015 for further details). The discontinuous model is then used to perform parameter studies on CLT properties. For all parameter studies the bending configuration is a panel supported on two sides and submitted to an evenly distributed load.

Shear effects. The slope variation of failure load trend as a function of panel's slenderness ratio (Fig. 1a) clearly separates the bending failure regime and the rolling-shear one. This leads to the identification of a transition slenderness of 15 for a 5-ply CLT and 19 for a 3-ply. The normalized difference between the predicted mid-span deflection and the one using the thin-plates theory quantifies the shear part in deflection as a function of slenderness ratio (Fig. 1b).

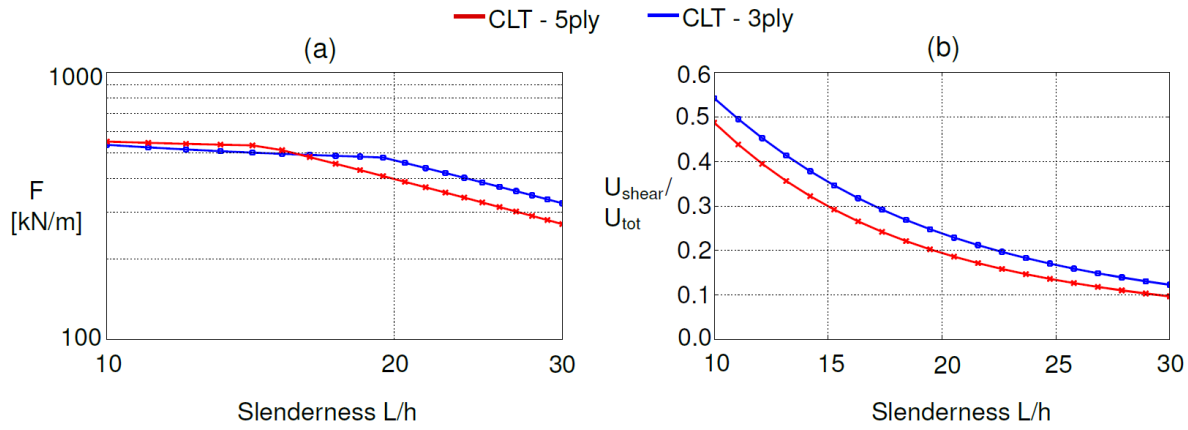


Figure 2 Shear effects on CLT in bending. Failure load trend (a) and shear contribution to mid-span deflection (b) as a function of panel's slenderness ratio

Number of layers. Figure 2 shows that, from a deterministic point of view, increasing layers' number for a fixed CLT total thickness yields lower failure load (Fig. 2a) and higher mid-span deflection (Fig. 2b). Both cases when the panel is thick and slender are presented. The oscillations in shear failure load trend (blue line in Fig. 2a) derive from the position of shear-compliant cross layers, which change with the lay-up.

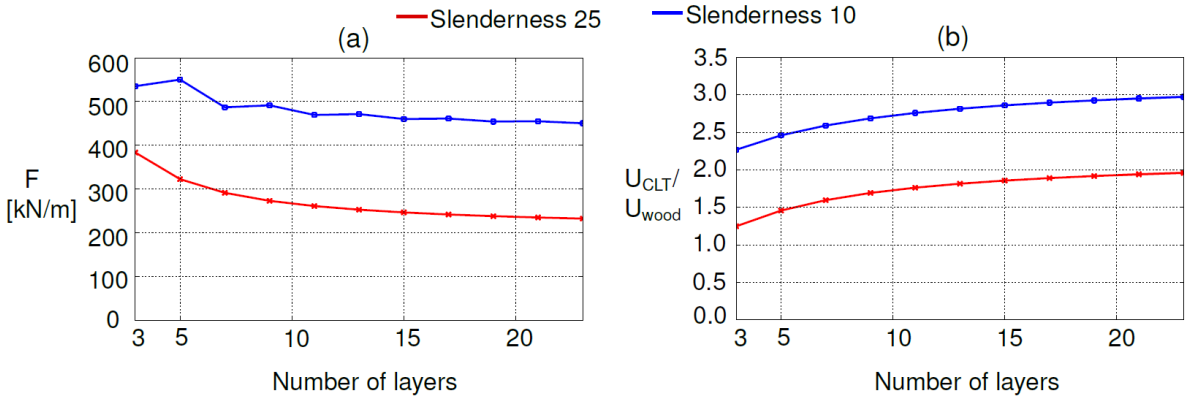


Figure 3 Decreasing CLT bending performance while enlarging the number of layers. Failure load (a) and normalized mid-span deflection (b)

Transverse layers' orientation. Intuitively, intermediate orientations of transverse layers between 90° and 0° may mitigate CLT shear weakness. Figure 3 presents the variation of mid-span deflection and failure load as a function of the varying orientation of 5-ply CLT transverse layers. Similar results are obtained for three or seven layers configurations. The favourable effects of rotating transverse layers are significant only for thick CLT panels, while for slender ones the gains are lower. Moreover, for both cases, the failure load trend shows a drastic drop at several lamination angles due to high in-plane shear stresses related to the torsion moment coming from the non-orthotropic configuration of the plate.

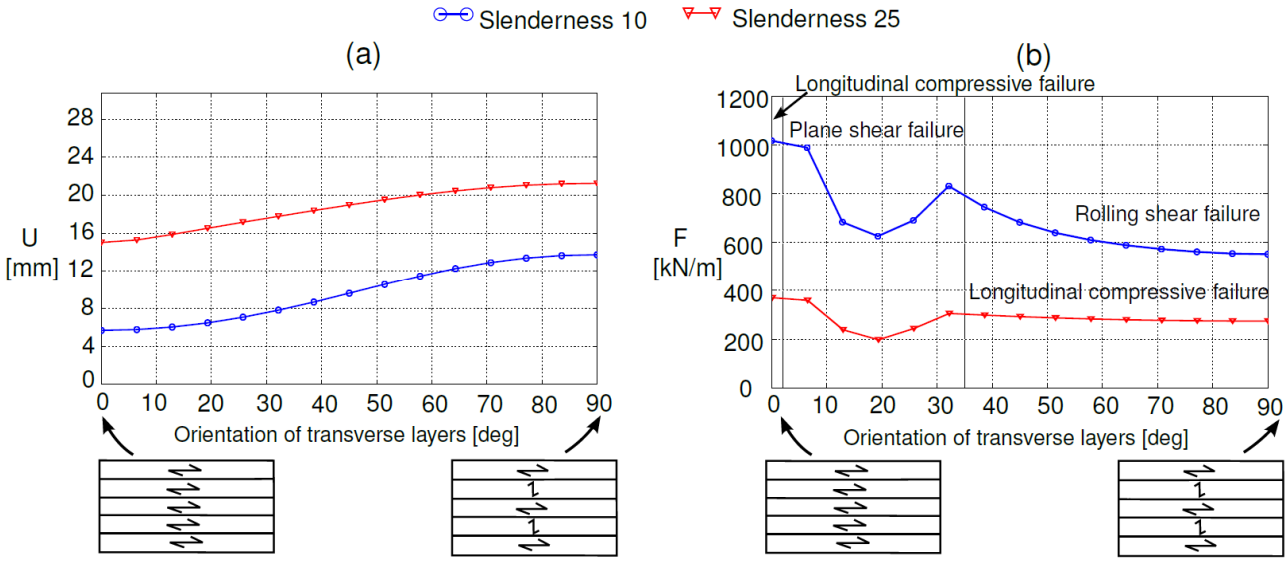


Figure 4 Mid-span deflection (a) and failure load (b) as a function of the varying orientation of transverse layers

3 Strong heterogeneities

Cross Laminated Timber panels having periodic spacing within each layer are already in production. The challenge is to assess the bending efficiency of these lighter and more acoustically efficient floors. Since they are innovative products and the knowledge about them is limited, an experimental campaign has been carried out. A modelling procedure in order to predict their bending behaviour, and especially transverse shear effects, is in development. In this section, the main results of the experiments and the first results of the modelling are presented and discussed.

3.1 Experimental campaign

3.1.1 Four-points bending tests on classical and innovative timber floors

The experimental campaign was based on four-points bending tests on classic and aerated CLT floors. The distance between the supports and the loading points was L/3 (where L is the span). The spaced floors had the same regular spacing between

boards along both direction and for all layers. The voids were filled with an insulating material (glass wool), having no mechanical properties. The wood species was Norway spruce of strength class S10 (DIN 4074) for the CLT panels and C24 (EN 338) for the spaced floors. Figure 5 and Table 2 present the geometry of the tested specimens as well as the main results.

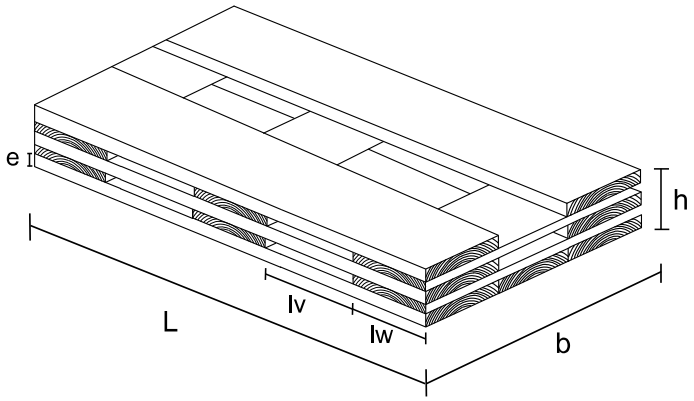


Figure 5 and Table 2 Geometry of the tested panels in four-points bending and main results

Configuration	**CLT**	**Panel-1**	**Panel-2**
Number of specimens	2	2	2
L (m)	4.65	5.88	5.88
b (m)	1.25	1.31	1.26
e (mm)	20	30	30
Number of layers	5	7	7
h (mm)	100	210	210
Voids length - lv (mm)	-	150	300
Wood length - lw (mm)	-	100	100
Wood volume (%)	100	40	25
Failure load (kN)	75	68	34
Failure mode	CL	TL	RS
Global stiffness (kN/m)	470	765	390
Bending stiffness (kN·m^2)	870	3100	1700
Shear / bending deflection (%)	3.5	15	25

Failure modes: RS = rolling shear; CL = longitudinal compressive; TL = longitudinal tensile

The measuring system was mainly based on linear variable differential transformers (LVDTs) for displacement measurement. For all specimens the global mid-span deflection (*U*) and the bending deflection (*u*) were measured. For some specimen, the absolute rotation (φ) of the plate's cross section was also measured. Then, the effective plate bending stiffness can be computed using the following equations:

$$(EI)_{flex} = \frac{F \cdot L_b^2 \cdot L}{48 \cdot u} \qquad (1) \qquad\qquad (EI)_{flex} = \frac{F \cdot L^2 \cdot \varphi}{18} \qquad (2)$$

where F is the load and L_b is the distance between the LVDTs used to measure the bending deflection *u*. Once the bending stiffness is determined, panel's shear stiff-

ness and shear contribution to deflection can be estimated by means of equations (3) and (4):

$$GA = \frac{F}{U} \cdot (EI)_{flex} \cdot \frac{216 \cdot L}{1296 \cdot (EI)_{flex} - 23 \cdot {}^{F}/_{U} \cdot L^3} \quad (3)$$

$$\frac{Shear\ deflection}{Bending\ deflection} = \frac{216 \cdot (EI)_{flex}}{23 \cdot GA \cdot L^2} \quad (4)$$

Additionally, the panel's failure load and failure mode were monitored. Table 2 shows the main results of the bending tests

Due to its high slenderness, the classical CLT floor failed in bending, with several ductile compressive cracks appearing in the upper layer before the brittle tensile failure of bottom layer. Both specimens of Panel-2 failed in rolling shear, with a significant rotation of transverse boards (Fig. 6), while the other configuration of spaced floors failed in tension in the bottom layer.

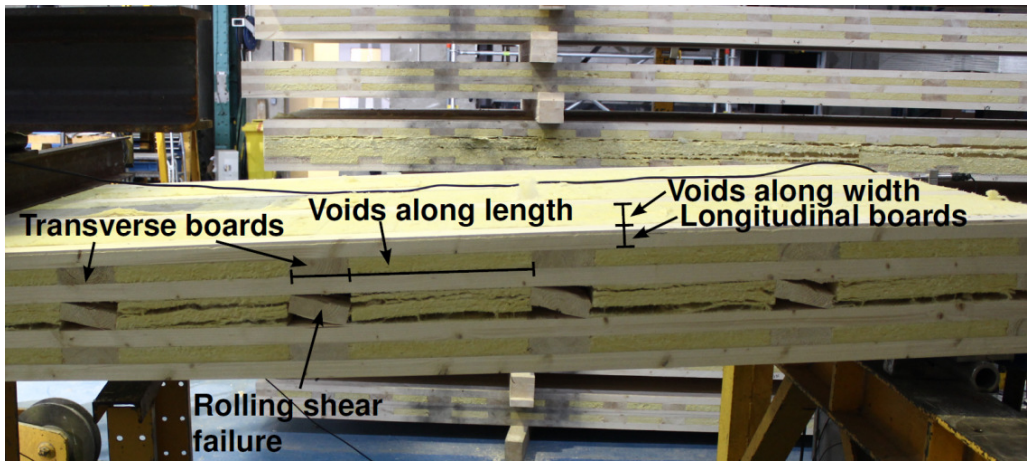
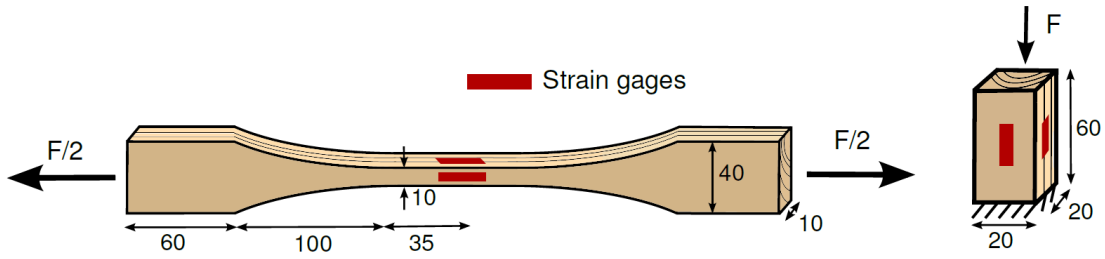


Figure 6 Rolling shear failure of transverse boards of spaced timber floors (Panel-2) in bending

3.1.2 Small-scale tests on clear raw timber

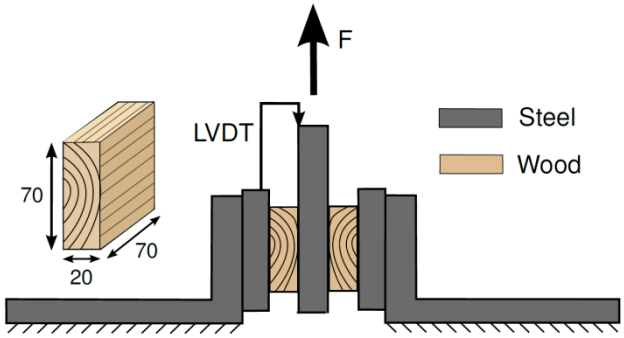
In order to mitigate the uncertainity on the mechanical properties for the subsequent modelling procedure, tests for the identification of elastic and strength properties of the raw timber are currently in progress. Axial-parallel to the grain (E_L, $f_{L,t}$, $f_{L,c}$) and rolling shear (G_{ZN}, f_{ZN}) tests have been carried out. The previous study (Franzoni et al, 2015) identified such mechanical properties as the dominant ones when dealing with bending behaviour of crosslams. Moreover, the mechanical properties of *clear* spruce have been found to be adequate to reproduce CLT bending response. Fig. 7-Table 4 and Fig. 8-Table 5 show the axial and shear tests on clear specimens of timber. The remaining elastic and strength properties for the

modelling are taken from Table 1. Classic crosslam floors and spaced ones have been supplied from two different producers; hence all results on the respective lumber boards are presented separately.



Axial Tests – Parallel to grain (L)	n	$\bar{x}$ (MPa)	COV (%)
Spaced floors-Norway spruce C24 (EN 338)			
E_{L} (tension + compression)	21	12700	17.2
$f_{L,t}$	10	85	17.3
$f_{L,c}$	8	51	6.4
CLT floors-Norway spruce S10 (DIN 4074)			
E_{L} (tension + compression)	17	9850	11.8
$f_{L,t}$	7	77	13.7
$f_{L,c}$	8	38	4.1

Figure 7 and Table 4 Geometry and results of the axial tests on clear wood. Dimensions in mm



Rolling Shear Tests (ZN)	n	$\bar{x}$ (MPa)	COV (%)
Spaced floors-Norway spruce C24 (EN 338)			
G_{ZN}	10	110	25
f_{ZN}	12	1.6	18
CLT floors-Norway spruce S10 (DIN 4074)			
G_{ZN}	8	70	25
f_{ZN}	8	1.3	9

Figure 8 and Table 5 Geometry and results of the shear tests on clear wood. Dimensions in mm

3.2 Advanced modelling and existing design methods

The bending tests on CLT panels allowed a further validation of the previously described equivalent-layer model. The deflections predicted at the same points of LVDTs lead to the identification of structure's elastic moduli using equations (1), (3)

and (4). Two existing design methods for CLT which allow the direct estimation of the bending stiffness are applied: the gamma-method (Eurocode 5, 2004) and the shear analogy method (Kreuzinger, 1999). Both of them are implemented following the instructions found in Gagnon & Pirvu, 2013. Table 6 shows the relative difference between the actual and predicted bending behaviour f CLT panels.

Table 6 Relative distances between the actual and predicted bending behaviour of CLT

Comparison - CLT	Gamma Method	Shear Analogy	Equivalent layer - discontinuous
Failure load	-	-	**+5%**
Failure mode	-	-	**CL**
Global stiffness	**-5%**	**-4%**	**-4%**
Bending stiffness	**-8%**	**-4.5%**	**-4.5%**
Shear / bending deflection	**-8.5%**	**+8%**	**-5.5%**

From Table 6 it is clear how both the suggested advanced model of equivalent-layer and design methods can reproduce well CLT bending response.

A starting point for analysing more heterogeneous CLT floors could be using the methods presented above and reducing wood mechanical properties by the wood volume fractions. This approach has been already used in Blass & Gorelacher, 2000 for the rolling shear modulus and is common in engineering practice.

A more accurate model for periodically spaced CLT panels is currently in development. This model is based on a homogenization scheme handled by a high-order plate theory (Lebée & Sab, 2012). Basically it enforces membrane, bending and shear strains on an elementary unit cell of the spaced crosslam panel (Fig. 9) and equalizes the elastic energy of such an unit cell to the elastic energy of the whole panel. This homogenization approach leads to the identification of panel's bending and shear moduli, which will be used by the plate theory for computing the stresses and displacements.

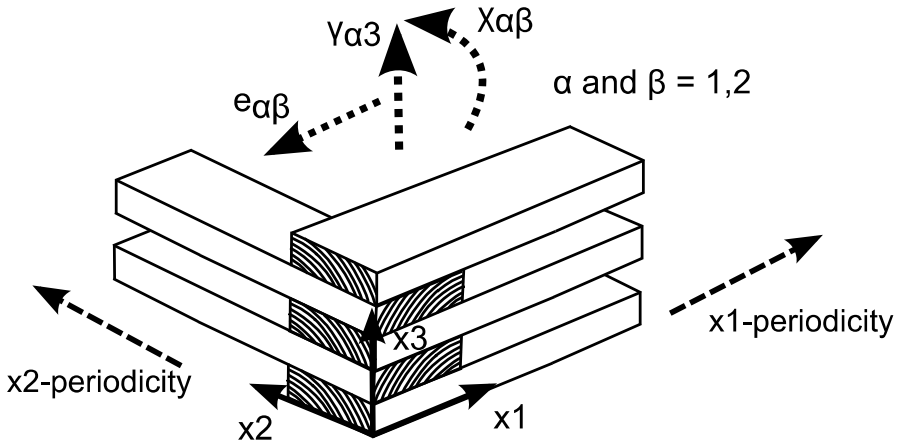


Figure 9 Unit cell of spaced CLT floors and imposed membrane (e), bending (χ) and shear (γ) strains

At present, only the membrane-bending step was conducted and therefore only the effective bending stiffness can be computed. Tables 7 and 8 present the distances between the actual and predicted behaviour of spaced floors. The equivalent-layer model predicts plate's moduli by means of equations (1), (3) and (4) using the predicted deflections, while the shear analogy method and the homogenization scheme compute directly the plate bending and shear stiffnesses. Due to the significant distance from the reference and from the other models, the gamma method is not presented and it is replaced by the periodic homogenization model.

Table 7 Relative distances between the actual and predicted bending behaviour of Panel-1

Comparison – Panel-1: wood volume = 40%	Shear Analogy*	Equivalent layer - discontinuous*	Periodic homogenization
Failure load	-	**+40%**	in progress
Failure mode	-	**RS**	in progress
Global stiffness	**+25%**	**+23%**	in progress
Bending stiffness	**+18%**	**+16%**	**-9.5%**
Shear / bending deflection	**-73%**	**-60%**	in progress

* Mechanical properties reduced by wood volume fraction

Table 8 Relative distances between actual and predicted bending behaviour of Panel-2

Comparison – Panel-2: wood volume = 25%	Shear Analogy*	Equivalent layer - discontinuous*	Periodic homogenization
Failure load	-	**+34%**	in progress
Failure mode	-	**RS**	in progress
Global stiffness	**+32%**	**+28%**	in progress
Bending stiffness	**+31%**	**+28%**	**+2%**
Shear / bending deflection	**-84%**	**-76%**	in progress

* Mechanical properties reduced by wood volume fraction

Table 7 and 8 shows that the wood volume fractions approach fails the more the panel becomes heterogeneous. The equivalent-layer model returns less margin of error than the design method. The advanced model based on periodic homogenization gives a good prediction of the effective bending stiffness of strongly heterogeneous panels.

4 Conclusion and outlooks

Low heterogeneities. The developed equivalent-layer model turned out to be appropriate to reproduce elastic and strength bending response of CLT panels. The edge-gluing of lateral boards does not contribute very much to the bending performance,

introducing an additional failure mode. The discontinuous layer model gives a better prediction of CLT load-carrying capacity than the continuous layer. Moreover, mechanical properties of clear wood lead to a good comparison with a reference specimen having knots. This suggests the “system effect” when assembling lumber boards in a CLT configuration, which effect is to regularize the presence of knots and increase boards stiffness and strength. The parameter studies performed with the validated model quantified shear effects in CLT in bending and showed the loss and low gains while enlarging the number of layers or the orientation of transverse layers.

Stronger heterogeneities. Reducing wood mechanical properties by wood volume fractions is not sufficient for a reliable design of spaced timber floors, especially with respect to transverse shear effects. This means that such a simplified approach cannot take into account the complexity of stress and strains distribution within these strongly heterogeneous panels. Therefore a more accurate model based on a homogenization scheme is currently in development. First results show that such an advanced model can precisely predict the bending stiffness of spaced floors. Therefore the following steps of this advanced modelling are the prediction of the panel’s shear modulus, deflection and failure load/mode. The final aim is to develop a simplified calculation tool for the design of heterogeneous CLT floors in order to encourage their safe application in timber construction.

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