STRUCTURAL ANALYSIS OF CROSS-LAMINATED GUADUA-BAMBOO (G-XLAM) PANELS USING DESIGN METHODS FOR CLT

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ABSTRACT

Densified lamellas of bamboo *Guadua angustifolia* Kunth (Guadua) were arranged orthogonally and glued together to form three- and five-layer cross laminated (XLam) panels with symmetrical compositions, which are refereed as G-XLam3 & G-XLam5, respectively. This XLam composition is typical of plywood and cross-laminated timber (CLT) panels, hence analytical design methods developed for these systems have been applied to analyse the structural performance of G-XLam panels. For structural analysis G-XLam panels were considered as multi-layered systems composed of contiguous lamellas with orthotropic axes orientated at 0° and 90°. Timber engineering methods normalized by international standards were used in this study for the prediction of the mechanical properties of G-XLam panels. Bending stiffness properties of these panels were predicted using the transformed cross section method to find the modulus of elasticity of beams from the moduli of elasticity of the individual layers. As the elastic properties of the laminate system depend on the elastic properties of the individual layers, the elastic parameters for small clear specimens obtained in previous studies were used for the numerical analysis of G-XLam panels. Furthermore, compression stiffness and shear stiffness of the G-XLam panels were also calculated. Compared to test results and finite elements (FE) models undertaken prior to this study, analytical values provided a reasonably accurate prediction of the elastic properties of G-XLam3 and G-XLam5 panels. Differences in the results are assumed to be caused by manufacture flaws and thickness variation within the individual lamellas. Overall, this study showcases the potential of using timber engineering methods for the structural analysis of novel engineered bamboo products as well as their potential for structural applications. This design method also enables the design and analysis of novel composite laminated structures combining the high density and high axial stiffness of densified bamboo lamellas with low grade softwood or low-density core materials.

KEYWORDS: (bamboo, timber engineering, cross-laminated timber, engineered bamboo products, plywood)

INTRODUCTION

The structural response under load of cross-laminated Guadua panels (G-XLam) depends on the mechanical properties of the material used to form the layers of the panel and the arrangement of layers to form the panel structure. In timber engineering, several methods have been used to analyse the mechanical response of multi-layered materials such as plywood and CLT (Bodig and Jayne, 1982; Ceccotti, 2008; BSI, 2010, 2011; Gagnon and Pirvu, 2011; BSI, 2014). The structural design of CLT is dictated by European standards (TRADA, 2009; BSI, 2010, 2011, 2014). Two of the calculation methods used for the determination of CLT design values for floor plates and wall panels in Eurocode 5 (BSI, 2014) are the theory of mechanically jointed beams and the composite theory method (TRADA, 2009). The former, also referred to as the Gamma method, considers layers acting only in the load direction connected by imaginary fasteners. The composite theory or 'k-method' based on plywood analysis theory, assumes that the longitudinal modulus of elasticity E_0 is thirty times the transverse modulus E_{90}. Both theories neglect shear deformation for span to width ratios ≥ 30.

As an alternative, BS EN 14272 (BSI, 2011) derives the mechanical properties of plywood panels in bending, compression and tension from the independent properties of rigidly connected layers and their transformed cross section. Thus, composite theory of laminated systems and equivalent section area are used for the prediction of the stiffness and strength values. This is in agreement with the method given by (Bodig and Jayne, 1982) for the analysis of multi-layered orthotropic wood laminates. A similar approach, known as the shear analogy, was developed by Kreuzinger (Blass et al. 1995) for calculating the stiffness and strength values of solid panels with cross-laminated layers in bending including those with span to width ratios less than 30. The BS EN 14272 procedure is widely accepted for the analysis of cross-laminated timber systems (Blass and Fellmoser, 2004; Ceccotti, 2008; Gagnon and Pirvu, 2011; Okabe *et al.*, 2013) and is used in this study for the prediction of the elastic properties of G-XLam panels in bending, compression and shear.

ANALYTICAL DESIGN METHODS FOR G-XLAM PANELS

The mechanical properties of G-XLam panels are dependent on the direction of applied stress, the arrangement of the individual layers that form the panel and the specific mechanical properties of the constituent material. A thermoset epoxy resin was used and assumption of a perfectly rigid connection between layers was made; thus, the effect of adhesive is neglected for the analysis of the elastic properties of G-XLam panels. Usually the lay-up of CLT and plywood is symmetrical, therefore, calculation of their mechanical properties is based on a mechanically symmetrical composition of alternated cross layers.

Determination of modulus of elasticity of the panels in bending (Ep_m)

For the determination of the G-XLam panel modulus of elasticity in bending (Ep_m), the gross section stiffness, $Ep_m \cdot I_0$ is equated to the sum of the second moments of area of the individual lamella stiffnesses. Ep_m is found (BS EN 14272) using the notation provided in **Error! Reference source not found.**, with the location of the neutral axis denoted $\bar{y}$, a panel has *n* lamellas; the origin is at top surface and all equations consider unit width (i.e., *b* = 1).

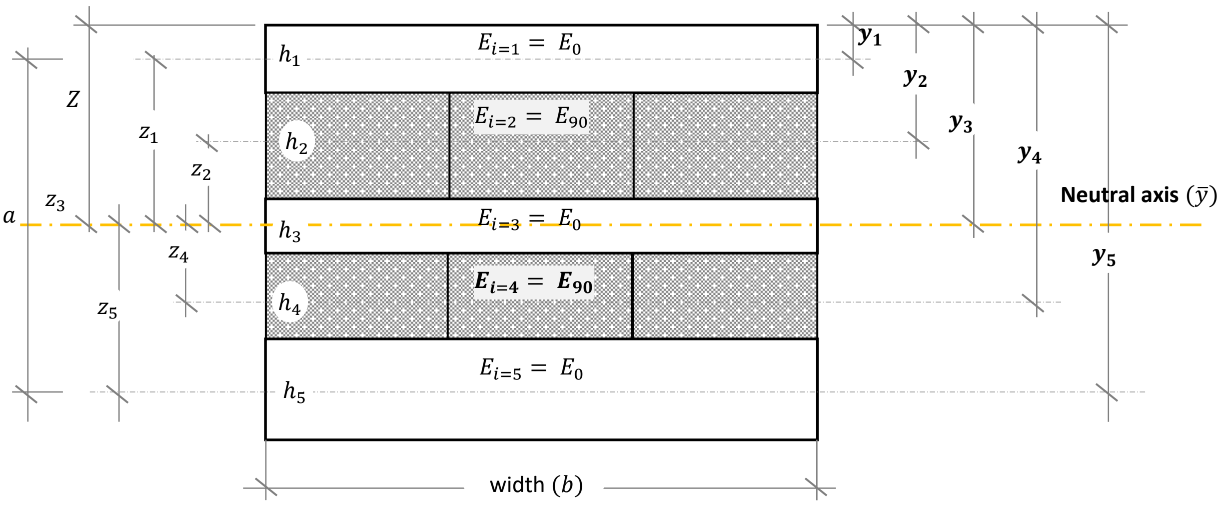


Figure 0-1. Typical cross section of a five-layer cross-laminated panel using the shear analogy method.

The location of the centroid of each lamella is:

$$y_i = \sum_{j=1}^{i-1} (h_j) + h_i/2$$

The location of the neutral axis of the transformed cross section is given as:

$$\bar{y} = \frac{\sum_{i=1}^{n} E_i h_i y_i}{\sum_{i=1}^{n} E_i h_i}$$

For the typical case of a symmetric section having an odd number of alternating lamellas:

$$\bar{y} = \frac{\sum_{i=1}^{n} h_i}{2}$$

The distance from the neutral axis to the centroid of each lamella is:

$$z_i = y_i - \bar{y}$$

The gross moment of inertia of the panel section is:

$$I_0 = \left(\frac{1}{12}\right) \sum_{i=1}^{n} h_1^3$$

The gross section flexural stiffness, $Ep_m I_0$ is equated to the sum of the second moments of area of the individual lamella stiffnesses. The equivalent gross section modulus, Ep_m, is:

$$Ep_m = \frac{\left(\frac{1}{12}\right) \sum_{i=1}^{n} E_i h_i^3 + \sum_{i=1}^{n} E_i h_i z_i^2}{I_0}$$

The elastic section moduli are:

$$S_0 = \frac{\left(\frac{1}{12}\right) \sum_{i=1}^{n} E_i h_i^3 + \sum_{i=1}^{n} E_i h_i z_i^2}{Ep_m \bar{y}}$$

$$S_n = \frac{\left(\frac{1}{12}\right) \sum_{i=1}^{n} E_i h_i^3 + \sum_{i=1}^{n} E_i h_i z_i^2}{Ep_m \left(\sum_{i=1}^{n} h_i - \bar{y}\right)}$$

For the typical case of a symmetric section having an odd number of alternating lamellas:

$$S_0 = \mathrm{S}_n = \mathrm{S} = \frac{\left(\frac{1}{12}\right) \sum_{i=1}^{n} E_i h_i^3 + \sum_{i=1}^{n} E_i h_i z_i^2}{Ep_m \bar{y}} = \frac{2 I_0}{\sum_{i=1}^{n} h_i}$$

The moment capacity of the panel is therefore:

$$M = fr_n S_n \leq fr_0 S_0$$

This assumes that failure of the extreme tension and/or compression fibres of the section constitute the moment limit state. For example, we can determine modulus of rupture from a permitted strain and assume that the outermost lamella is longitudinally oriented:

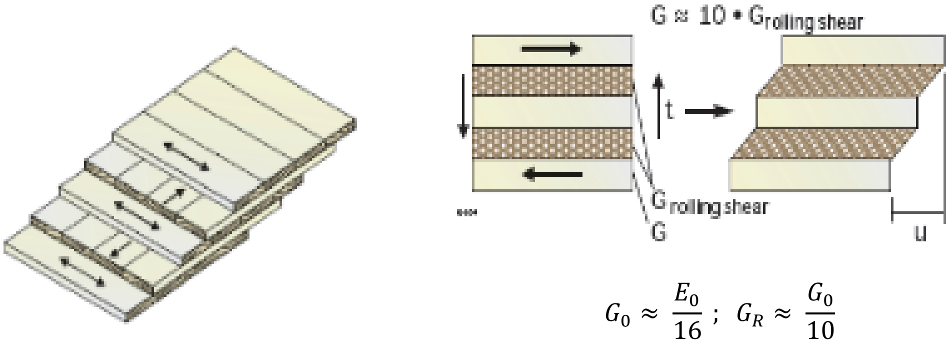
$$f_{rT} = E_0 \varepsilon_T \quad and \quad f_{rC} = E_0 \varepsilon_C$$

BS EN 338 (BSI, 2009) and BS EN 14272 (BSI, 2011) assume that the modulus of elasticity in bending of the longitudinal layers ($E_{0,m}$) is 30 times greater than the moduli of elasticity in bending of the cross layers ($E_{90,m,t,c}$) for softwood and 15 times greater for hardwood.

Other gross section material properties are similarly obtained using transformed section properties.

Determination of the panel shear modulus

In timber engineering, the shear modulus parallel to the grain (G_0) for softwood CLT panels is generally considered to range between 1/12 and 1/20 of the longitudinal modulus of elasticity of the panel (E_0) and typically assumed to be 1/16 of E_0. Furthermore, the shear modulus perpendicular to grain known also as the rolling shear modulus (G_R) is assumed to be 1/10 of G_0 (Gagnon and Pirvu, 2011) (Figure 0-2).



$$G_0 \approx \frac{E_0}{16}\ ; \ \ G_R \approx \frac{G_0}{10}$$

Figure 0-2. Shear modulus parallel (G_0) and perpendicular to grain (G_R) of a cross laminated panel. Image by (Gagnon and Pirvu, 2011).

The gross section shear modulus is:

$$G_{12} = \frac{\sum_{i=1}^{n-1} G_{12i} \cdot h_i}{\sum_{i=1}^{n-1} h_i} \quad and \quad G_{21} = \frac{\sum_{i=1}^{n-1} G_{21i} \cdot h_i}{\sum_{i=1}^{n-1} h_i}$$

where $_{12}$ is in the plane of the section shown and $_{21}$ is out of plane.

Determination of the modulus of elasticity in compression and tension of cross-laminated panels.

The MOE of cross laminated panels in compression and tension ($Ep_{t,c}$) can be calculated according to BS EN 14272 (BSI, 2011). The gross section in-plane tension and compression moduli are:

$$Ep_t = \frac{\sum_{i=1}^{n-1} E_{t,i} \cdot h_i}{\sum_{i=1}^{n-1} h_i} \quad and \quad Ep_c = \frac{\sum_{i=1}^{n-1} E_{c,i} \cdot h_i}{\sum_{i=1}^{n-1} h_i}$$

$Ep_{t,c}$ is equal to the summation of the elastic properties of the compound layers in the panel and assumption of one unit of width is also made in this equation.

Prediction of the elastic properties of G-XLam panels using stiffness values from their individual constituting layers.

Calculation of the elastic properties of three- and five-layer cross-laminated Guadua (G-XLam3 & G-XLam5) panels in compression (Ep_c), shear (G_{12}) and bending (Ep_m) was undertaken using the equations above. The moduli of elasticity in bending parallel ($Ep_{m,0}$) and perpendicular ($Ep_{m,90}$) to the direction of outer skins of the panels (considered as the main direction) are calculated. An exemplary calculation of $Ep_{m,0}$ for a G-XLam3 and G-XLam5 panel can be seen in Figure 0-3 and Figure 0-4, respectively.

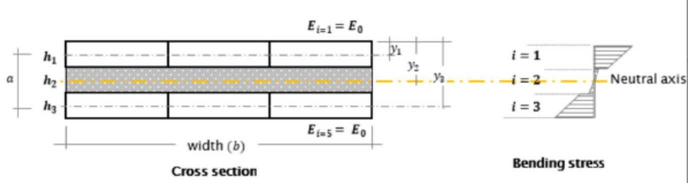
Furthermore, the moduli of elasticity in compression along the longitudinal ($Ep_{c,0}$) and transverse ($Ep_{c,90}$) axes, and the in-plane shear modulus (G_{12}) are calculated. Values obtained previously for E_0, E_{90} and G_o (G_{12}) through testing of small clear specimens (Archila *et al.*, 2014; Archila, Ansell and Walker, 2014) were used as the characteristic properties of the individual layers in the three and five layers cross laminated panels (G-XLam3 and G-XLam5).

For the calculations, mostly the notation system from BS EN 14272 (BSI, 2011) has been adopted and related to the methodology herein presented, which were used for calculating the elastic properties of the G-XLam panels as explained below:
$A_i = h_i \cdot b_i \cdot E_i$; where $b = 1$;

$I_i = A_i \cdot \frac{h_i^2}{12} = \sum_{i=1}^{n} E_i \cdot \frac{h_i^3}{12}$ and $J_i = A_i \cdot C_i = \sum_{i=1}^{n} E_i \cdot \frac{h_i^3}{12}$ in (kN.mm^2);

$C_i = z_i^2$ in mm^2; $Ep_m \cdot \mathrm{I} = Ep_m \cdot \frac{h_i^3}{12} = 12 \cdot \frac{\sum_{i=1}^{n} I_i + J_i}{\sum_{i=1}^{n} h_i^3}$; where $\mathrm{I} = \frac{b \cdot h_i^3}{12}$

and, for the panel shear modulus (G_{12}): $N_i = h_i \cdot G_{vi}$; where G_{vi} refers to the shear modulus of the individual layers.



Type of panel: G-XLam5
2 L + 1 T layers THM modified Guadua
Calculation including cross layers

$Ep_{m.0-\text{G-XLam3 (2L + 1T)}}$

$$Ep_m = \frac{12 \cdot \sum_{i=1}^{n} E_i \cdot h_i \cdot z_i^2 + \sum_{i=1}^{n} E_i \cdot h_i^3}{(\sum_{i=1}^{n} h_i)^3}$$

$E_0 = 21.74\ kN/mm^2$

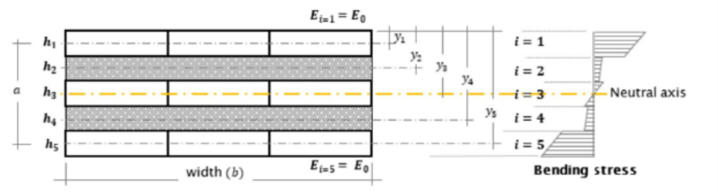
$E_{90} = 1.02\ kN/mm^2$

$G_0 = 1.32\ kN/mm^2$

G-XLam3		thickness	Property	A_i	T_i	Y_i	B_i	z_i	C_i	I_i	J_i
		h_i	E_i	$h_i * b_i * E_i$	$t_{i-1}+T_{i-1}$	$T_i + t_i/2$	$A_i * Y_i$	$\lvert Z_{ax} - Y_i \rvert$	z_i^2	$A_i * h_i^2/12$	$A_i * C_i$
Layers	Grain	(mm)	(kN/mm²)	(kN)	(mm)	(mm)	(kN*mm)	(mm)	(mm)²	(kN.mm²)	(kN.mm²)
h_1	L, (0°)	5.70	21.74	123.87	0.00	2.85	352.85	5.70	32.46	335.05	4,020.58
h_2	T, (90°)	5.70	1.02	5.81	5.70	8.55	49.66	0.00	0.00	15.72	0.00
h_3	L, (0°)	5.70	21.74	123.87	11.39	14.24	1,764.27	5.70	32.46	335.05	4,020.58
$\sum_{i=1}^{n} =$		**17.09**		**253.55**			**2,166.79**			**685.81**	**8,041.16**

$z_{ax} = \frac{\sum_{i=1}^{n} B_i}{\sum_{i=1}^{n} A_i}$	8.55 mm (z_{ax} = 17.09/2)	I = **415.95 mm⁴**	$Ep_m \cdot I$ = **8,726.97 kN.mm²**	**Ep_m = 20.97 kN/mm²**

Figure 0-3. Calculation of the bending modulus of elasticity ($Ep_{m,0}$) of a G-XLam3 panel with main fibre-direction along its length (E_0) based on the elastic properties of all its compounding layers (2L, E_0 + 1T, E_{90}) and on a unit of width.



Type of panel: G-XLam5
3 (L) + 2 (T) layers THM modified Guadua
Calculation including cross layers

$Ep_{m.0-\text{G-XLam5 (3L + 2T)}}$

$$Ep_m = \frac{12 \cdot \sum_{i=1}^{n} E_i \cdot h_i \cdot z_i^2 + \sum_{i=1}^{n} E_i \cdot h_i^3}{(\sum_{i=1}^{n} h_i)^3}$$

$E_0 = 21.74\ kN/mm^2$

$E_{90} = 1.02\ kN/mm^2$

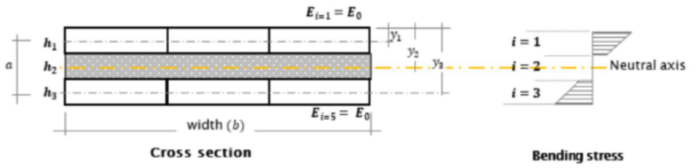
$G_0 = 1.32\ kN/mm^2$

G-XLam5		thickness	Property	A_i	T_i	Y_i	B_i	z_i	C_i	I_i	J_i
		h_i	E_i	$h_i * b_i * E_i$	$t_{i-1}+T_{i-1}$	$T_i + t_i/2$	$A_i * Y_i$	$\lvert Z_{ax} - Y_i \rvert$	z_i^2	$A_i * h_i^2/12$	$A_i * C_i$
Layers	Grain	(mm)	(kN/mm²)	(kN)	(mm)	(mm)	(kN*mm)	(mm)	(mm)²	(kN.mm²)	(kN.mm²)
h_1	L, (0°)	5.25	21.74	114.15	0.00	2.63	299.63	10.50	110.25	262.18	12,584.54
h_2	T, (90°)	5.25	1.02	5.36	5.25	7.88	42.17	5.25	27.56	12.30	147.60
h_3	L, (0°)	5.25	21.74	114.15	10.50	13.13	1,498.16	0.00	0.00	262.18	0.00
h_4	T, (90°)	5.25	1.02	5.36	15.75	18.38	98.40	5.25	27.56	12.30	147.60
h_5	L, (0°)	5.25	21.74	114.15	21.00	23.63	2,696.69	10.50	110.25	262.18	12,584.54
$\sum_{i=1}^{n} =$		**26.25**		**353.15**			**4635.05**			**811.13**	**25,464.28**

$z_{ax} = \frac{\sum_{i=1}^{n} B_i}{\sum_{i=1}^{n} A_i}$	13.13 mm (z_{ax} = 26.25/2)	I = **1,507.48 mm⁴**	$Ep_m \cdot I$ = **26,275.41 kN.mm²**	**Ep_m = 17.43 kN/mm²**

Figure 0-4 Calculation of the bending modulus of elasticity ($Ep_{m,0}$) of a G-XLam5 panel with main fibre-direction along its length (E_0) based on the elastic properties of all its compounding layers (2L, E_0 + 1T, E_{90}) and on a unit of width.

Bending strength of the panels (fp_m) was calculated as the sum of the strengths of the individual layers and using results of MOR_b obtained from small clear specimens testing in (Archila *et al.*, 2014; Archila, Ansell and Walker, 2014). For this calculation, cross layers (E_{90}) were not taken into account and a symmetrical composition of the cross laminated (G-XLam) panel was assumed.



Type of panel: G-XLam5

2 (L) + 1 (T) layers THM modified Guadua
Calculation including cross layers

$Ep_{m,0-\ \text{G-XLam3 (2L)}}$

$$Ep_m = \frac{12 \cdot \sum_{i=1}^{n} E_i \cdot h_i \cdot z_i^2 + \sum_{i=1}^{n} E_i \cdot h_i^3}{\left(\sum_{i=1}^{n} h_i\right)^3}$$

$E_0 = 21.74\ kN/mm^2$

$E_{90} = 0.00\ kN/mm^2$

$G_0 = 1.32\ kN/mm^2$

G-XLam3		thickness	Property	A_i	T_i	Y_i	B_i	z_i	C_i	I_i	J_i
		h_i	E_i	$h_i * b_i * E_i$	$t_{i-1}+T_{i-1}$	$T_i + t_i/2$	$A_i * Y_i$	$\lvert Z_{ax} - Y_i \rvert$	z_i^2	$A_i * h_i^2/12$	$A_i * C_i$
Layers	Grain	(mm)	(kN/mm²)	(kN)	(mm)	(mm)	(kN*mm)	(mm)	(mm²)	(kN.mm²)	(kN.mm²)
h_1	L, (0°)	5.70	21.74	123.87	0.00	2.85	352.85	5.70	32.46	335.05	4,020.58
h_2	T, (90°)	5.70	0.00		5.70						
h_3	L, (0°)	5.70	21.74	123.87	11.39	14.24	1,764.27	5.70	32.46	335.05	4,020.58
$\sum_{i=1}^{n} =$		**17.09**		**247.74**			**2,117.13**			**670.10**	**8,041.16**

$z_{ax} = \frac{\sum_{i=1}^{n} B_i}{\sum_{i=1}^{n} A_i}$ 8.55 mm ($z_{ax} = 17.09/2$)	$I =$ **415.95 mm⁴**	$Ep_m \cdot I =$ **8,711.25 kN.mm²**	$Ep_m =$ **20.94 kN/mm²**
$MOR_i = 190.38\ N/mm^2$	$Z = \frac{\sum_{i=1}^{n} h_i}{2} = 8.55$ mm	$fp_m = \frac{12 \cdot \sum_{i=1}^{n} MOR_i \cdot h_i \cdot z_i^2 + \sum_{i=1}^{n} MOR_i \cdot h_i^3}{\left(\sum_{i=1}^{n} h_i\right)^3} \cdot \frac{\sum_{i=1}^{n} h_i}{2 \cdot Z}$	fp_m **= 183.33 N/mm²**

Figure 0-5 Calculation of the bending modulus of elasticity (Ep_m) of a G-XLam5 panel with main fibre-direction along its length (E_0) based on the elastic properties of all its compounding layers (2L, E_0 + 1T, E_{90}) and on a unit of width.

Finally, z_{ax} (kN.mm^2) in symmetrical panel compositions is $T/2$ (half the total thickness of the panel); z_i is the distance between the centre point of each layer and the central axis and Y_i is the distance between the external face and the central axis of each layer in (mm), as illustrated in **Error! Reference source not found.**.

RESULTS AND DISCUSSION

A summary of all the predicted elastic values for G-XLam panels in bending (Ep_m), compression (Ep_c) and shear (G_v) obtained are presented in

.

Table 1. Predicted elastic values for G-XLam panels in bending, compression and shear.

Property	Main direction of layers	Symbol	G-XLam 3		G-XLam 5	
			2L,E_0+1T,E_{90}	2L,E_0	3L,E_0+2T,E_{90}	2L,E_0
Bending	Longitudinal (L)	$Ep_{m,0}$	**20.97 GPa**	20.94 GPa	**17.43 GPa**	17.22 GPa
	Transverse (T)	$Ep_{m,90}$	1.79 GPa	0.98 GPa	5.33 GPa	0.81 GPa
Bending strength	Longitudinal (L)	fp_m	-	183.33 MPa	-	150.78 MPa
Compression	Longitudinal (L)	$Ep_{c,0}$	**14.83 GPa**	14.49 GPa	13.45 GPa	13.05 GPa
	Transverse (T)	$Ep_{c,90}$	7.93 GPa	0.68 GPa	9.31 GPa	0.61 GPa
Shear	-	G_{12}	**0.92 GPa**	0.88 GPa	0.84 GPa	0.79 GPa

L = main load direction (longitudinal) & T = 90° to the main load direction (transverse

As can be seen, no-significant contribution to the stiffness of the panels is given by the cross layers (those transversally orientated or at 90º to the main direction of the panel). A very small influence of the rolling shear (G_R) on the mean panel modulus of rigidity (G_v) is also observed. Overall, G_v calculations including G_R presented an improvement in axial stiffness between 5% and 6%, while stiffness values in the longitudinal direction of G-XLam panels in bending are about 35% higher than those in compression. Similar behaviour for structural and non-structural wood panels is reported by BSI (2008) and Marcroft (2012). This reduction in the elastic properties in compression can be explained by the effects of shear and buckling during in-plane loading.

Bending strength (fp_m) values predicted for G-XLam3 and G-XLam5 panels were 183.33MPa and 150.78MPa, respectively. These results overestimate the actual capacity of the panel, as the MOR values of the individual layers used for this calculation were obtained from three-point bending tests. As showcased in Table 2, elastic values in bending, compression and shear calculated for G-XLam panels are generally higher than the mean values of conventional structural and non-structural wood products.

Table 2. Mean elastic values of structural and non-structural wood panels (all values in GPa).

Property (GPa)	Main layer direction (external)	Symbol	Multilay. solid wood panels [a] (20-30mm)	Birch plywood [b] (8.5-25mm)	CLT 3	CLT 5	CLT M1 BSP (C24) [c] crossplan	G-XLam 3 2L +1T	G-XLam 5 3L +2T
Bending modulus	0º (L)	Ep_m	8.2	9.7	-	-	11.6	**20.97**	**17.43**
	90º (T)	$Ep_{m,90}$	0.55	6.1	-	-	0.37	1.79	5.33
Compression modulus	0º (L)	$Ep_{c,0}$	3.5	9	7.42	6.74	-	**14.83**	13.45
	90º (T)	$Ep_{c,90}$	2.9	7.9	3.91	4.62	-	7.93	9.31
Shear modulus	-	G_{12}	0.47		-	-	0.65	**0.92**	0.84

[a] (BSI, 2008); [b] (Marcroft, 2012); [c] (Mayr-Melnhof Kaufmann Group, 2009).

CONCLUSIONS

Given the mechanical properties of the individual components (layers) of the panelised system G-XLam, its bulk mechanical behaviour could be predicted through different mathematical expressions that consider the variation of number of layers, orientation, thickness and mechanical properties of the individual layers. These formulae are based on analytical design methods for plywood and CLT that are accepted by international standards, including European and Canadian standards.

Stiffness values obtained using this design method provide design values for structural design with an adequate match with test results using physical (contact) measurement techniques performed by (Archila *et al.*, 2017). Currently, multiple laminations with engineered bamboo that achieve comparable sections to structural timber products result in overengineered products, which are costly and have a higher carbon footprint. This lack of competitiveness has been a barrier to the mainstream use of engineered bamboo products in structural applications. Analytical methods like the one developed in this research can aid the design of hybridised engineered bamboo products mixed with weaker and cheaper lamellas that achieve the same performance of structural timber products such as CLT, whilst maintaining an effective section, a competitive cost and a low carbon footprint.

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