COST Action FP1407 2nd Conference
"Innovative production technologies and increased wood products recycling and reuse"
Brno, Czech Republic
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ELASTIC PROPERTIES OF THERMO-HYDRO-MECHANICALLY MODIFIED BAMBOO (*Guadua angustifolia* Kunth) MEASURED IN TENSION

Dr Hector F. Archila
Visiting Researcher UoBath
& Amphibia Group's CEO

Outline

1. Why densification and engineered bamboo?
2. Research @ Bath
3. Results & Discussion
4. Conclusions

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Amphibia base
Hector F. Archila
hector.archila@bath.edu

Densification

- Thermo-hydro-mechanical (THM) modifications -

WOOD MODIFICATION

Chemical modification	Etherification, Olification, Acetylation, Furfurylation, Formaldehydation, etc.	
Thermo-Hydro (TH) modifications	Wood drying	
	Wood ageing	
	Heat treatment	Thermowood
		Plato Wood
		Retification & Perdure
		Oil Heat Treatment (OHT)
	Reconstituted wood	Composites
		Fibre webs
		Veneer processing
		Biomass processing
Thermo-Hydro-Mechanical (THM) modifications	Bending	Solid wood
		Laminated wood
	Wood shaping	Surface
		Cross-sectional
	THM densification	Open system (TM & THM)
		Closed system (THM)
	Wood welding	

Heat, pressure and water interact to achieve:

- ✓ **Changes in shape (e.g. bending)**
- ✓ **Improve weather resistance**.
- ✓ **Reduce fungi decay and hygrospicity**.

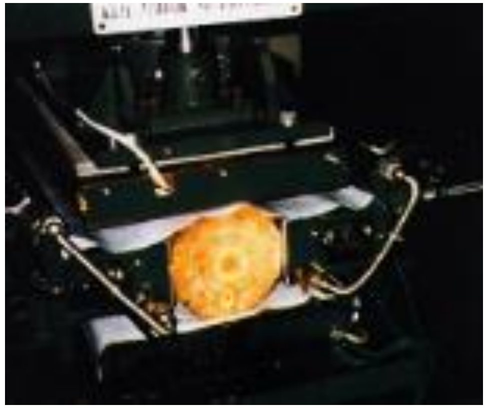
- ✓ **Increase in density, elastic properties & hardness** (by reducing void cellular spaces –cond. vessels, parenchyma) **without cell damage** (Sandberg & Kutnar, 2014).

Hector F. Archila
hector.archila@bath.edu

THM modifications

- *Wood and bamboo* -

Round log of wood prior to shaping



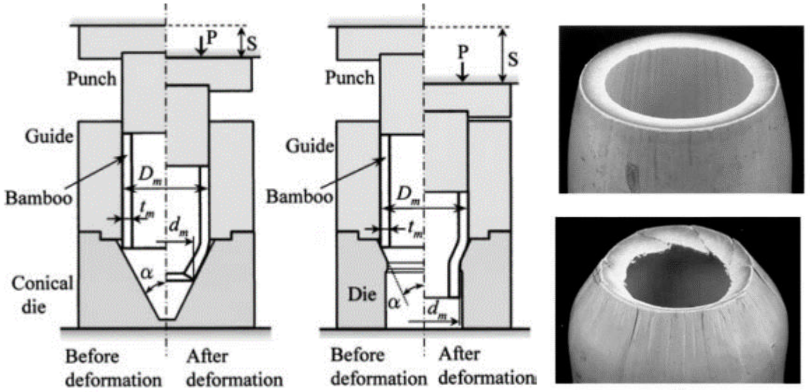
Squared log post-shaping.

Wood shaping
Photograph by Morsing (2000).

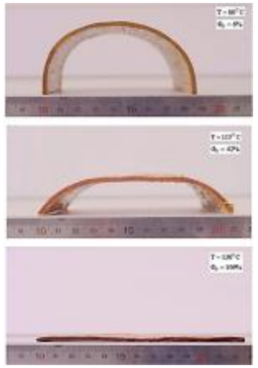
Bending round bamboo with a gas flame burner and green Guadua by manual force (www.guaduabamboo.com)

Bent Guadua construction temporary built in Pereira by Simon Velez.

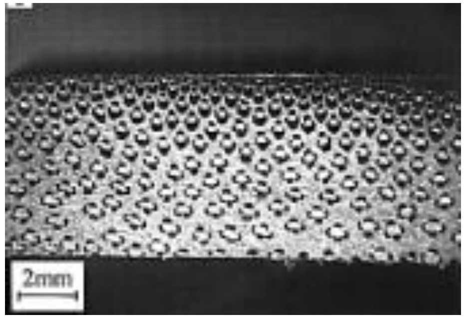
Bamboo bending



Bamboo shaping (nosing) (Kitazawa et al., 2004)



Oil Heat Treatment
(Kitazawa et al., 2004)



Open TM Densification (Li et al., 1994).

Hector F. Archila
hector.archila@bath.edu

Engineered Bamboo

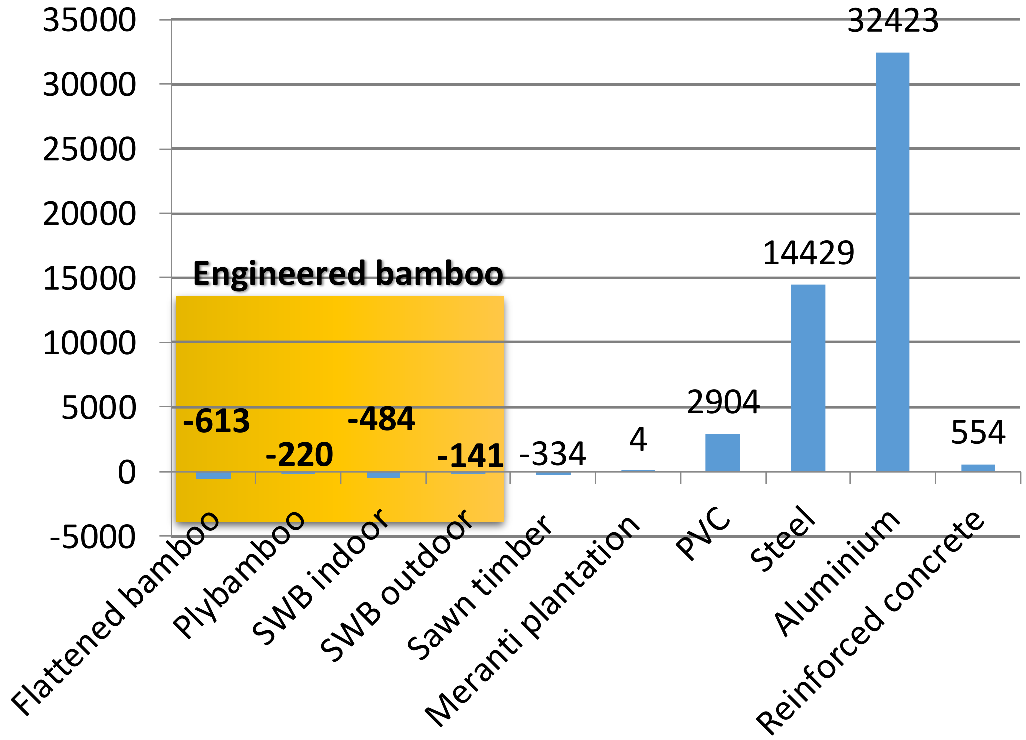
-full potential of the plant-

- ✓ Long lasting Value Added products
- ✓ Exploit mechanical properties
- ✓ Reduce labour, transport and wastage (30-50%)
- ✓ Overcome natural defects & shape irregularities
- ✓ Standardisable & lower CO2 emissions products.

Strand Woven Bamboo Flooring
Source BothBest Enterprise Co., Ltd

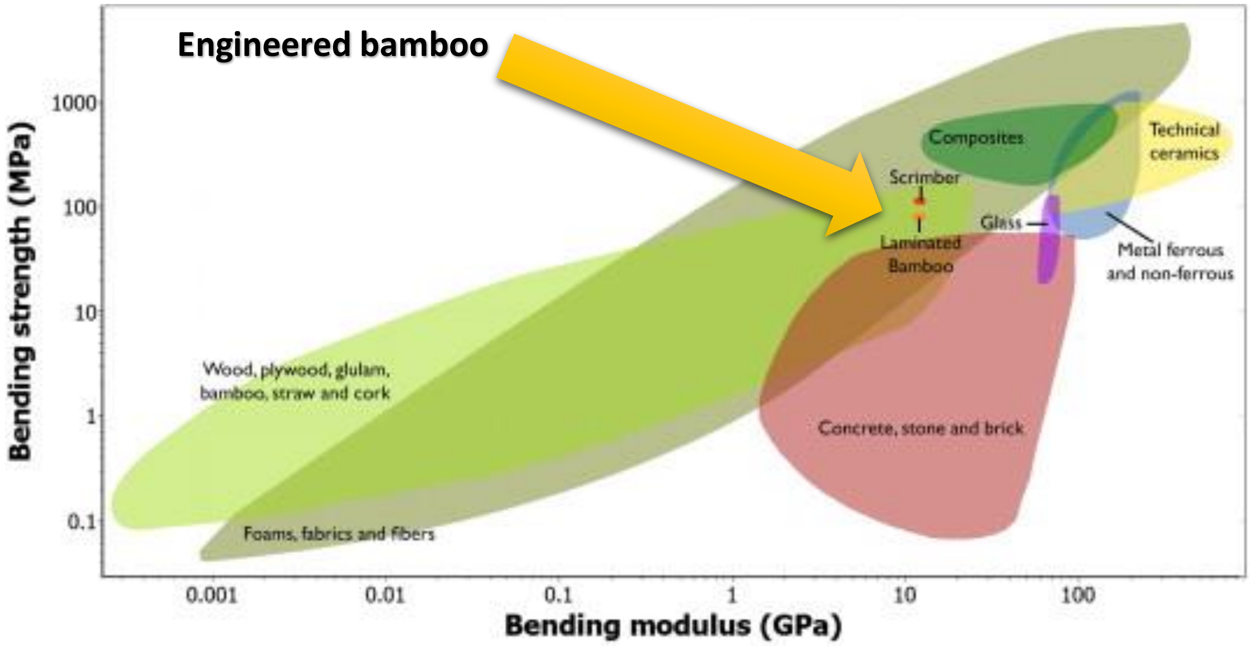
Hector F. Archila
hector.archila@bath.edu

✓ Carbon Footprint over life cycle ($kgCO2eq /m^3$)



Carbon Footprint over life cycle (kgCO2eq / m3 building material) for various common building materials (this report, Idemat 2014 database and Vogtländer et al. 2014).
Source: Inbar Technical report No. 35, 2014 by Vogtländer & van der Lugt

✓ Bending modulus vs. bending strength for various construction materials



Sharma, B., Gatóo, A., Bock, M. and Ramage, M., 2015. Engineered bamboo for structural applications. Construction and Building Materials, 81, pp. 66-73.

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Hector F. Archila
hector.archila@bath.edu

Research @ U-Bath

- ✓ **THM Densification**
- ✓ **Mechanical testing** (densified bamboo)
- ✓ **Results and discussion**

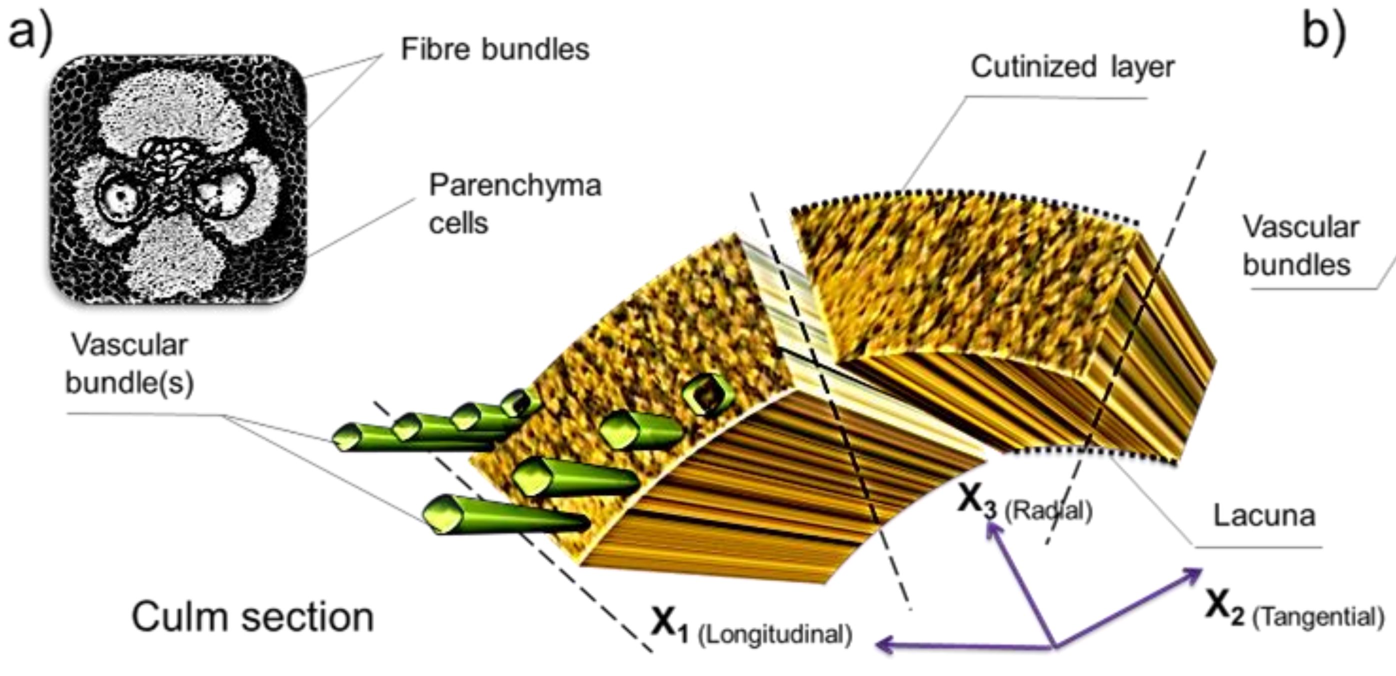
Hector F. Archila
hector.archila@bath.edu

Problem

50% wastage
Loss of stiffness
Labour & Energy intensive

Solution

Less wastage (20%)
Improved stiffness (2x*)
Straight-forward processing



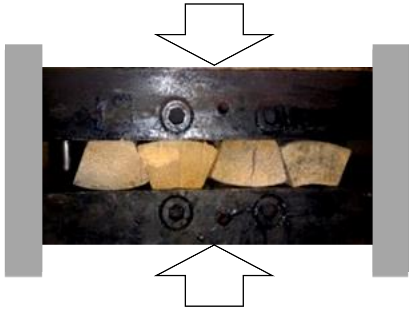
Hector F. Archila
hector.archila@bath.edu

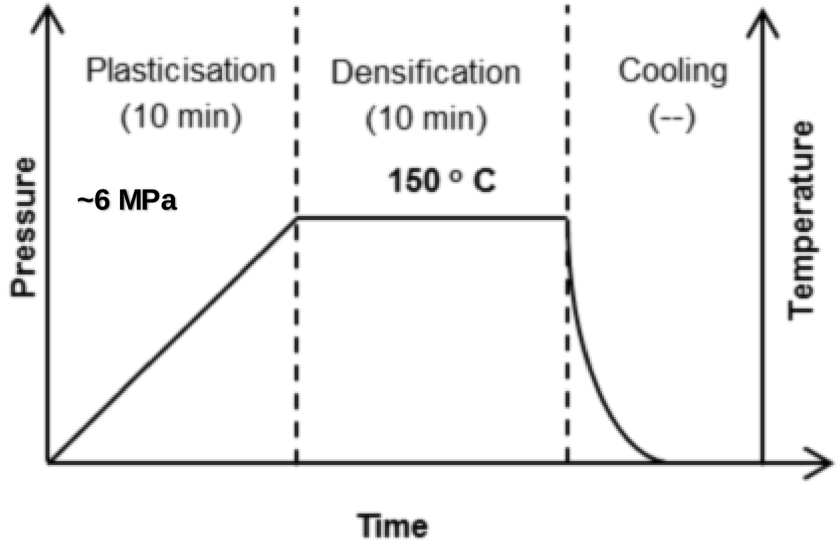
Densification Technology

-full potential of the plant-

Moisture + Pressure + Temp = THM treatment

Soaked bamboo - MC > 25% (FSP)



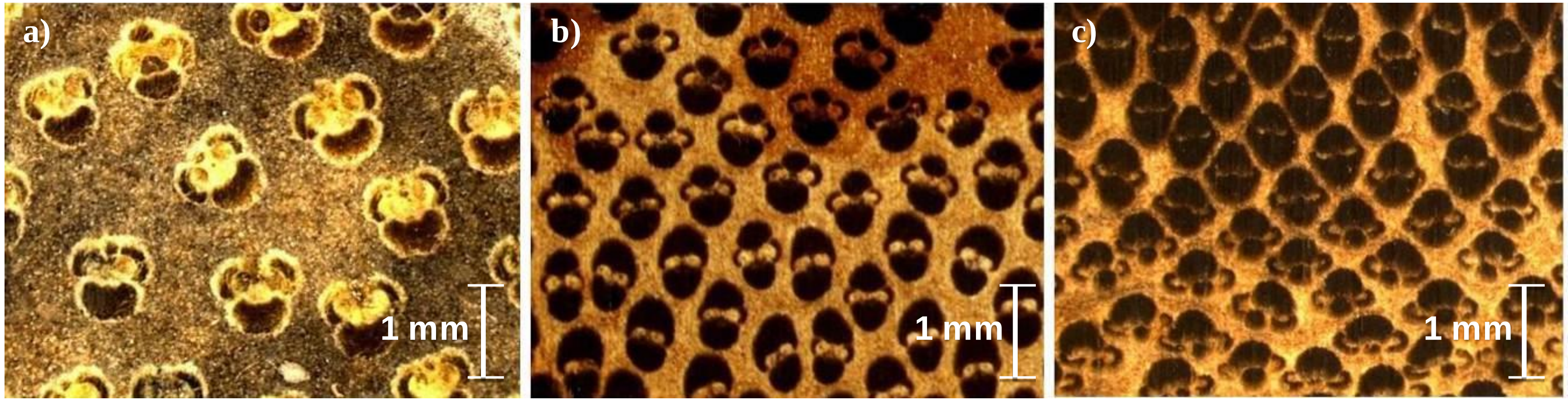


Bamboo → **Strips** → **Densified strips**

Hector F. Archila
hector.archila@bath.edu

Materials

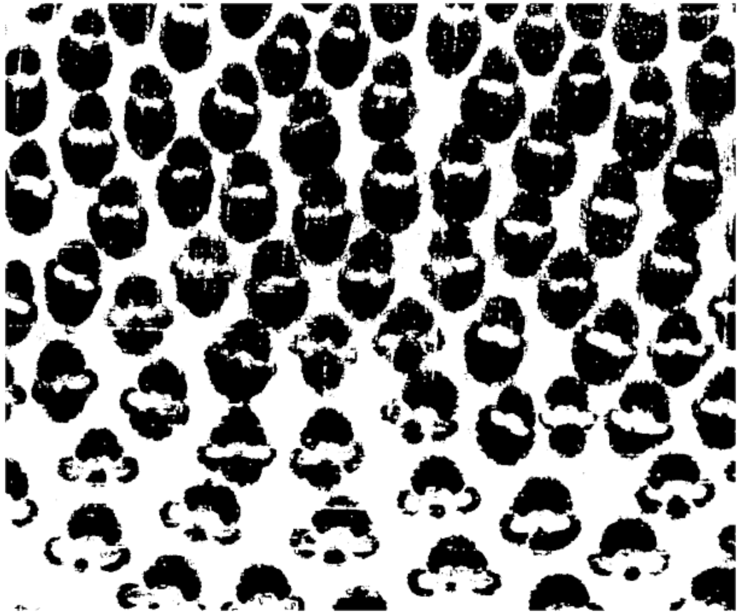
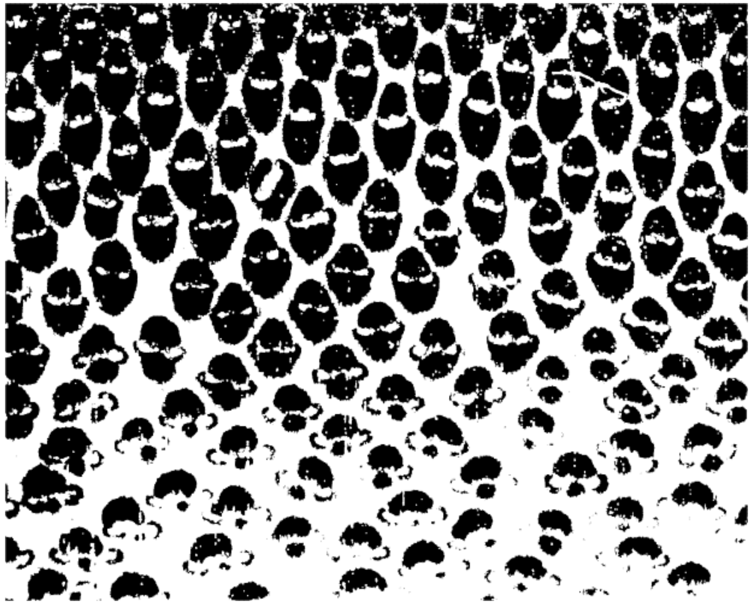
	Samples A Raw un-processed	Samples B Hot pressed + Dried	Samples C Pre-soaked + Hot pressed + Dried
Time	0	20 min	20 min
Pressure	0	60 kg/cm^2	60 kg/cm^2
Temperature	0	150^o C	150^o C
Compress. Set (C)	0	46.08%	42.51%
Oven dried density	0.54 g/cm^3	0.81 g/cm^3	0.89 g/cm^3



Hector F. Archila
hector.archila@bath.edu

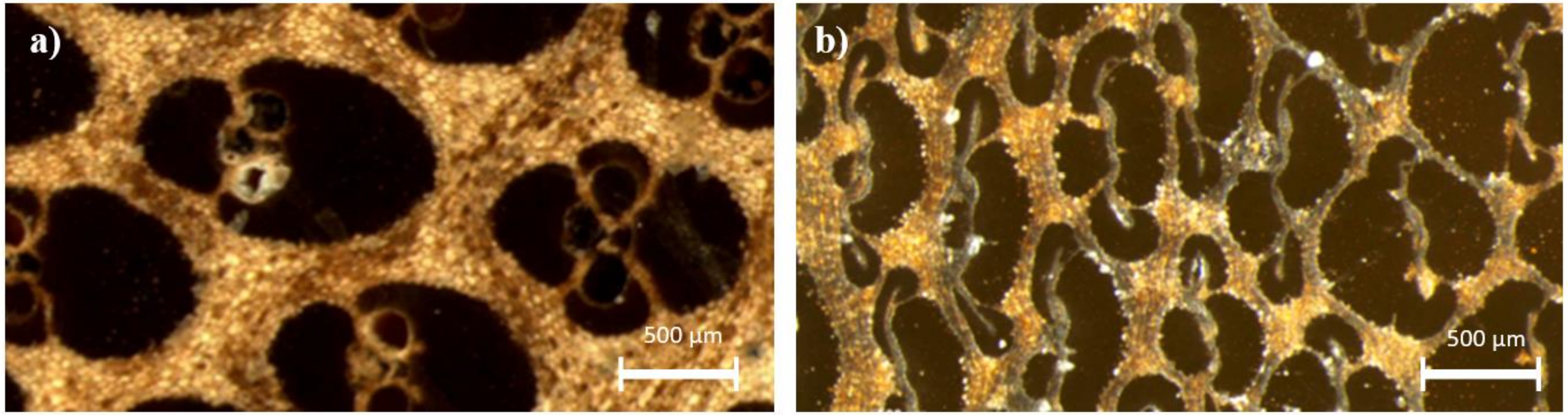
Image-J Analysis

Fibre's surface area

Samples A Raw un-processed	Samples B Hot pressed + Dried	Samples C Pre-soaked + Hot pressed + Dried
		
25.53 %	**45.57 %**	**47. 78 %**

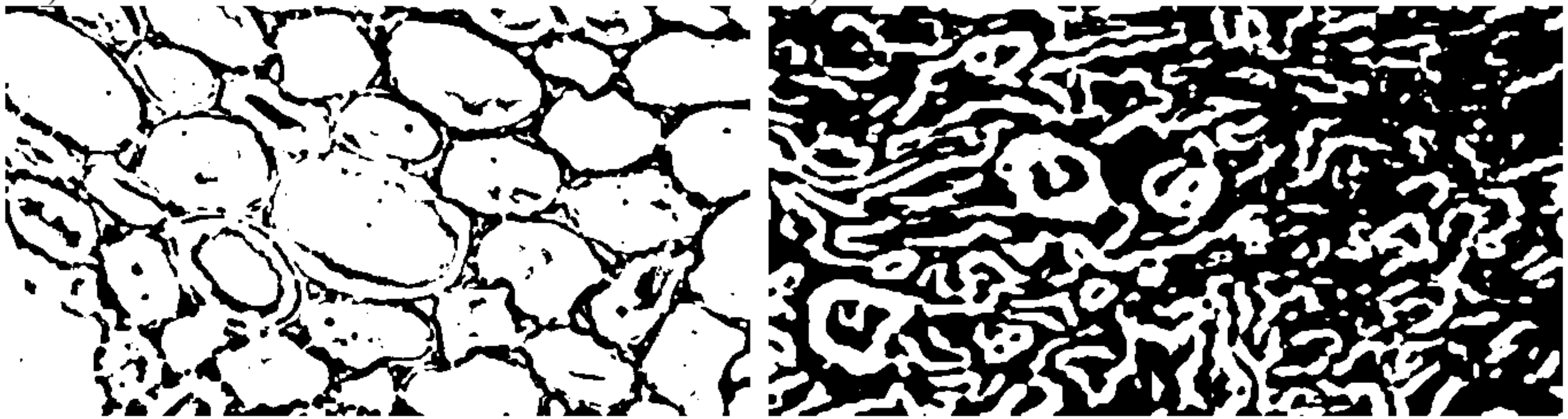
Hector F. Archila
hector.archila@bath.edu

Microscopy and Image analysis



Stereo microscope images
(a) before densification and
(b) following THMT.

a) b)



Digitally contrasted pictures *from two inverted reflected-light microscope images of the same region before (a) and after (b) densification.*

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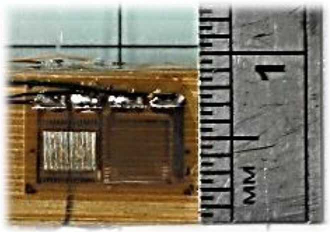
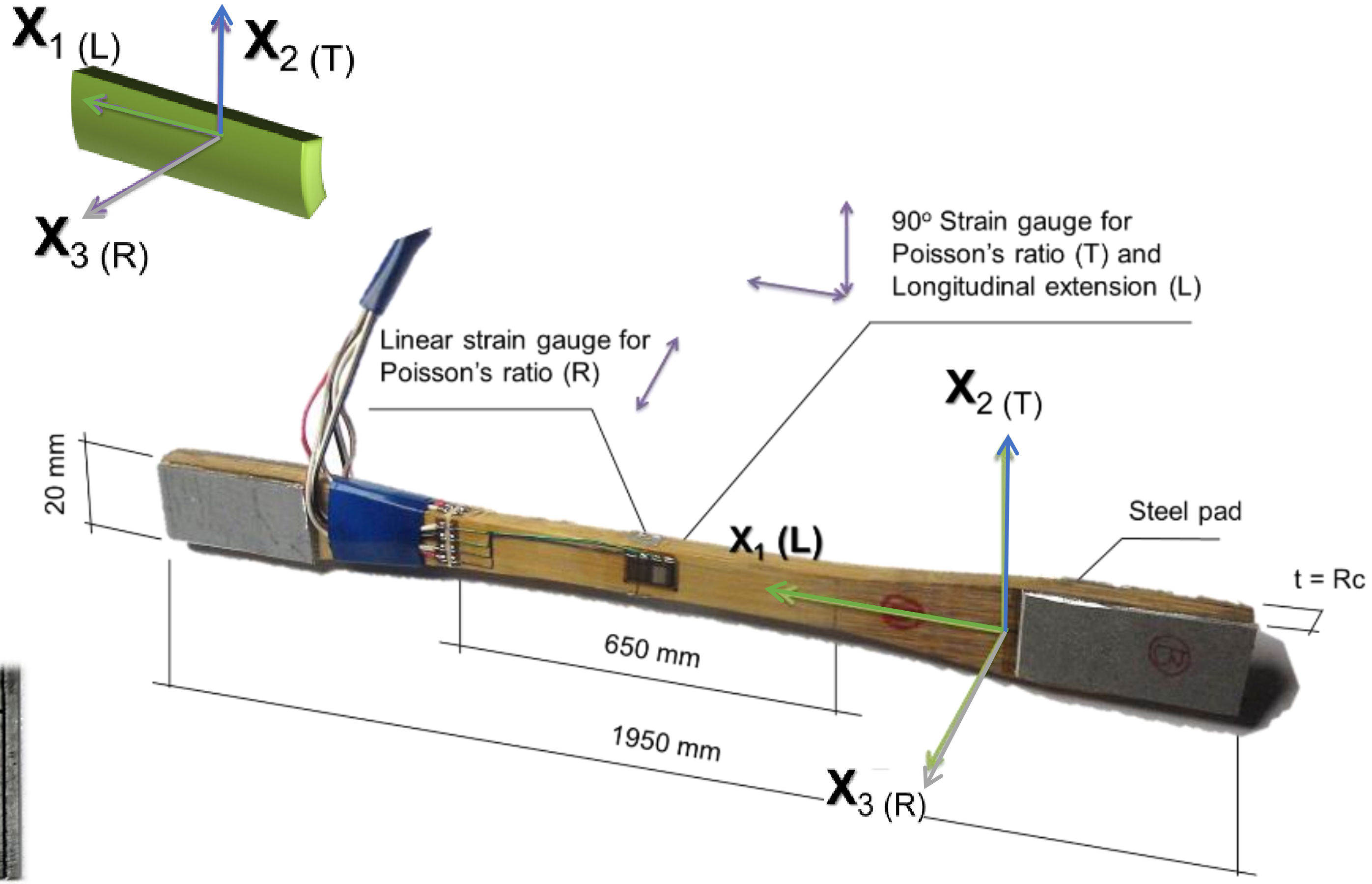
Amphibia base
Hector F. Archila
hector.archila@bath.edu

Longitudinal Tensile test

Elastic parameters MOE and V of small clear specimens

- ✓ *Samples conditioned at 27±2° C and RH of 70±5% for 20 days (MC=12%).*
- ✓ *Load limited to elastic deformation.*
- ✓ *Rate 0.5mm/min (all tests)*
- ✓ *Strain gauges, resistance 350 ohms.*
- ✓ *Four specimens per sample.*
- ✓ *(BS 373 / BS EN 408)*





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Hector F. Archila
hector.archila@bath.edu

Material characterization

Elastic stress versus strain plots for longitudinal loading

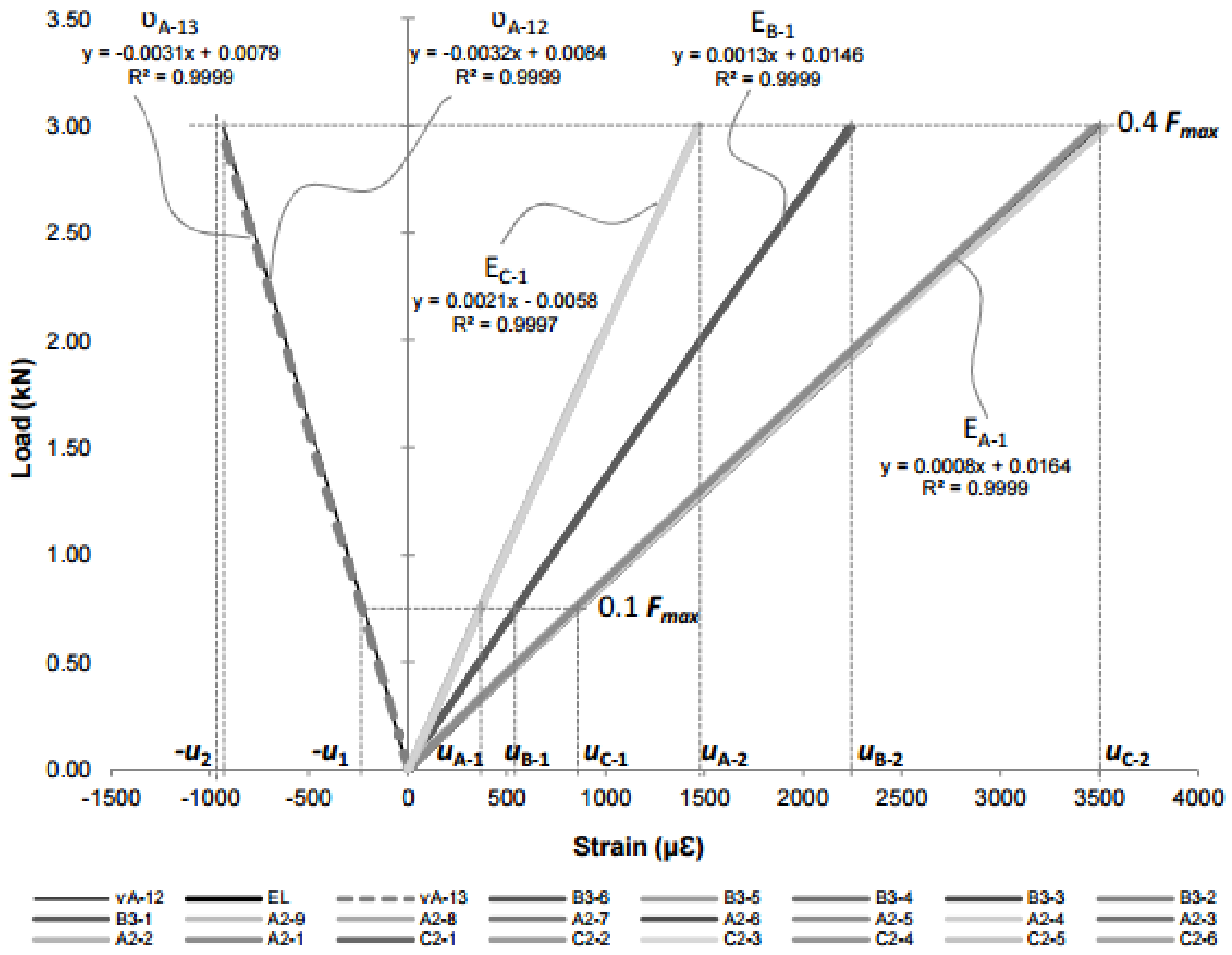


Figure 7-4. Typical initial load-strain graph for samples A, B and C under longitudinal tensile test. The portion of the graph between 0.1 $\boldsymbol{F}_{\max}$ and 0.4 $\boldsymbol{F}_{\max}$ was used for the linear regression analyses and values within this portion and a correlation coefficient $R^2 \geq 0.99$ were used for calculating υ_{13}, E_{12} and υ_{12} for all samples.

$$E_t = \frac{(F_2 - F_1)}{(u_2 - u_1) \cdot A}$$

is the increase of load between 0.1 $\boldsymbol{F}_{\max}$ and 0.4 $\boldsymbol{F}_{\max}$

$\cdot\ u_1)$ is the increase of deformation corresponding to $(F_2 - F_1)$ using the linear regression line.

$$\upsilon_{12} = -\frac{\varepsilon_2}{\varepsilon_1}$$

Poisson's ratio in the 1-2 plane caused by a load applied along X_1.

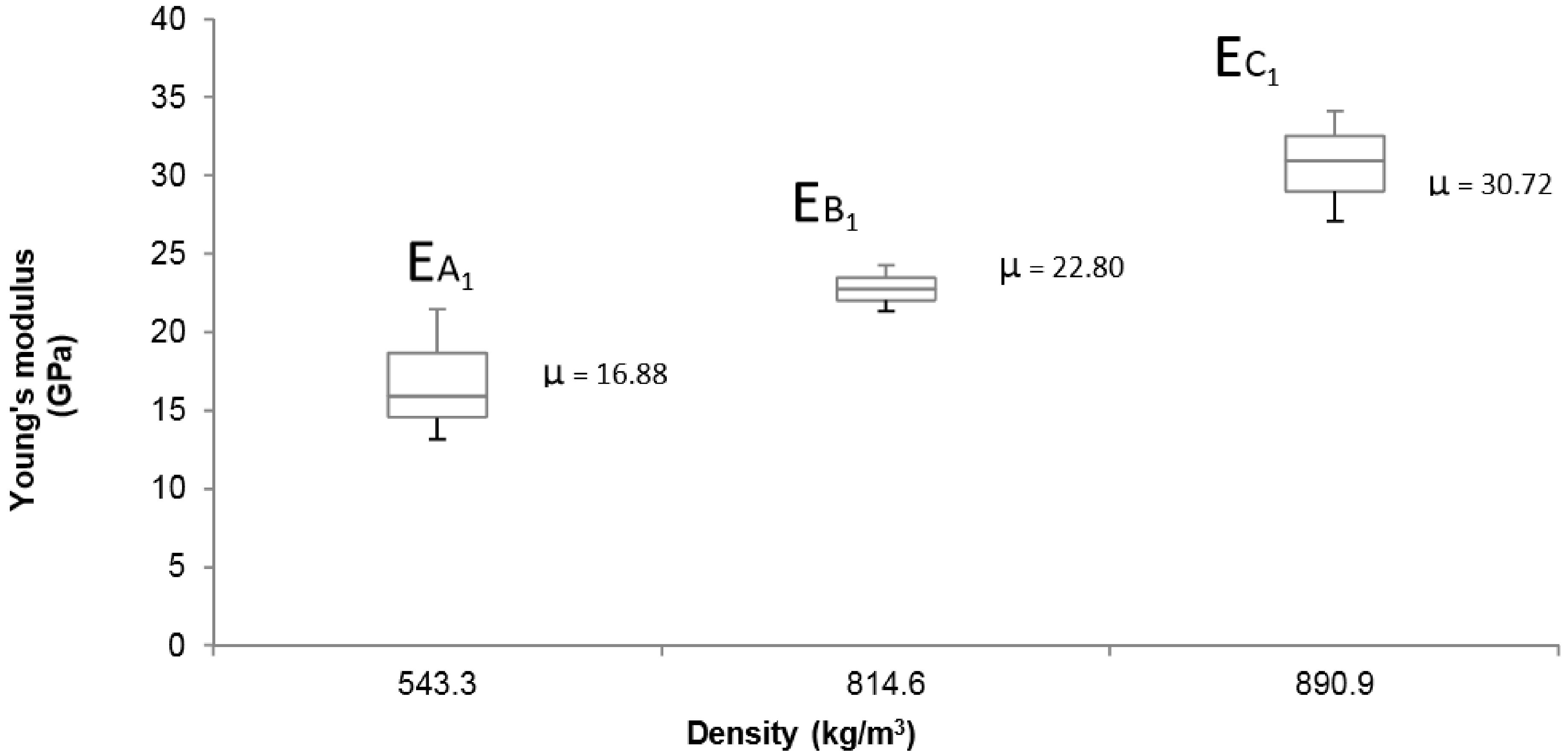
$$\upsilon_{13} = -\frac{\varepsilon_3}{\varepsilon_1}$$

Poisson's ratio in the 1-3 plane caused by a load applied along X_1.

Hector F. Archila
hector.archila@bath.edu

Material characterization

Box plot of the Young's modulus longitudinal to the direction of the fibres (E_1) of samples A, B and C.



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Hector F. Archila
hector.archila@bath.edu

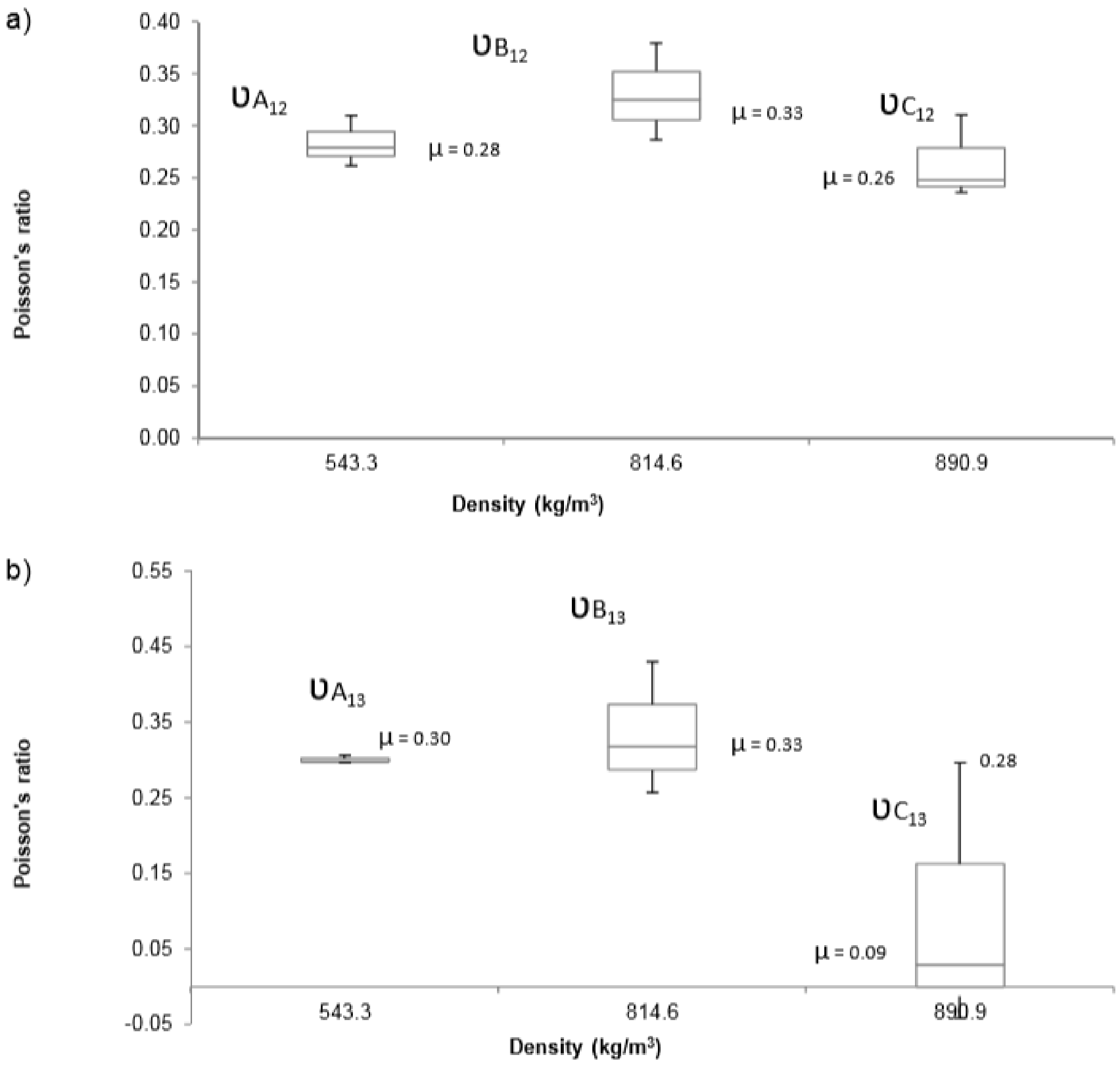

Figure 7-7. Box plots of the Poisson's ratios υ_{12} (a) and υ_{13} (b) of samples A, B and C.

Poisson's ratios υ_{12} vs density

Poisson's ratios ratio of passive strain along the tangential direction (X_2) to active strain along the longitudinal direction (X_1).

Poisson's ratios υ_{13} vs density

Poisson's ratios ratio of passive strain along the radial direction (X_3) to active strain along the longitudinal direction (X_1).

Hector F. Archila
hector.archila@bath.edu

Testing of densified strips

Elastic parameters MOE, G and V of individual layers

Property	Pre-THM (Control)		Post-THM (densified)	
$E_{L\ (Tension)}$	**16.88** ± **0.33 GPa**	**22.80** ± **0.73 Gpa**	**30.72** ± **0.43 GPa**	**~ 2x**
V_{LT}	0.28 ± 0.01	0.33 ± 0.01	0.26 ± 0.04	
CoV	3%	4%	2%	
V_{LR}	0.30 ± 0.02	0.33 ± 0.02	0.09 ± 0.02	
CoV	5%	5%	18%	
Compression set (C)	0 %	46.08 %	42.51 %	**~ 2x**
Density (ρ)	**543.3 kg/m³**	**814.6 kg/m³**	**890.9 kg/m³**	
Fibre surface	**25.53%**	**45.57%**	**47.78%**	
Specific stiffness (av.)	31.06 m^2s^{-2}	27.99 m^2s^{-2}	34.49 m^2s^{-2}	

Hector F. Archila
hector.archila@bath.edu

Conclusions

- ✓ THM modifications increased the physical and mechanical properties of bamboo Guadua with minimal damage to the cell structure.
- ✓ Values of mechanical properties of non-treated samples of Guadua (Sample A) obtained from the testing programme are in accord with those reported in the literature (García et al., 2012; Ghavami & Marinho, 2005; Rusinque & Takeuchi-Tam, 2007; Takeuchi-Tam & González, 2007).
- ✓ The coefficient of variation (CoV) for the obtained results is in the range of variation for the mechanical properties of clear wood; as defined by FPL (2010) CoV for the modulus of elasticity measured in tension parallel to the grain is 25%.
- ✓ υ_{21} and υ_{31} are very small and less precisely determined due to their high scattering of results; research conducted by Ling et al . (2009) on the determination of the **Poison's ratios of wood in compression** found similar issues.

Hector F. Archila
hector.archila@bath.edu

Děkuji, Thanks,...!
&
Questions...?

Hector F. Archila
Barch, PGDPM, PhD
hector.archila@bath.edu

Structural engineered bamboo

Manufacture of cross laminated Guadua panels (G-XLam)

Densified strips

- ✓ Epoxy resin content ~4% (Sicomin SR 5550) @ Spreading rate = 215 g/m^2
- ✓ Cold pressed ~ 35 kg/cm^2 *

G-XLam 5
t = 27.5 ± 1.5 mm (~1 inch)

G-XLam 3
t = 16.5 ± 0.9 mm (~0.6 inch)

G-XLam panels (3-5 layers)
(max 1,20 x 1,20 m)**

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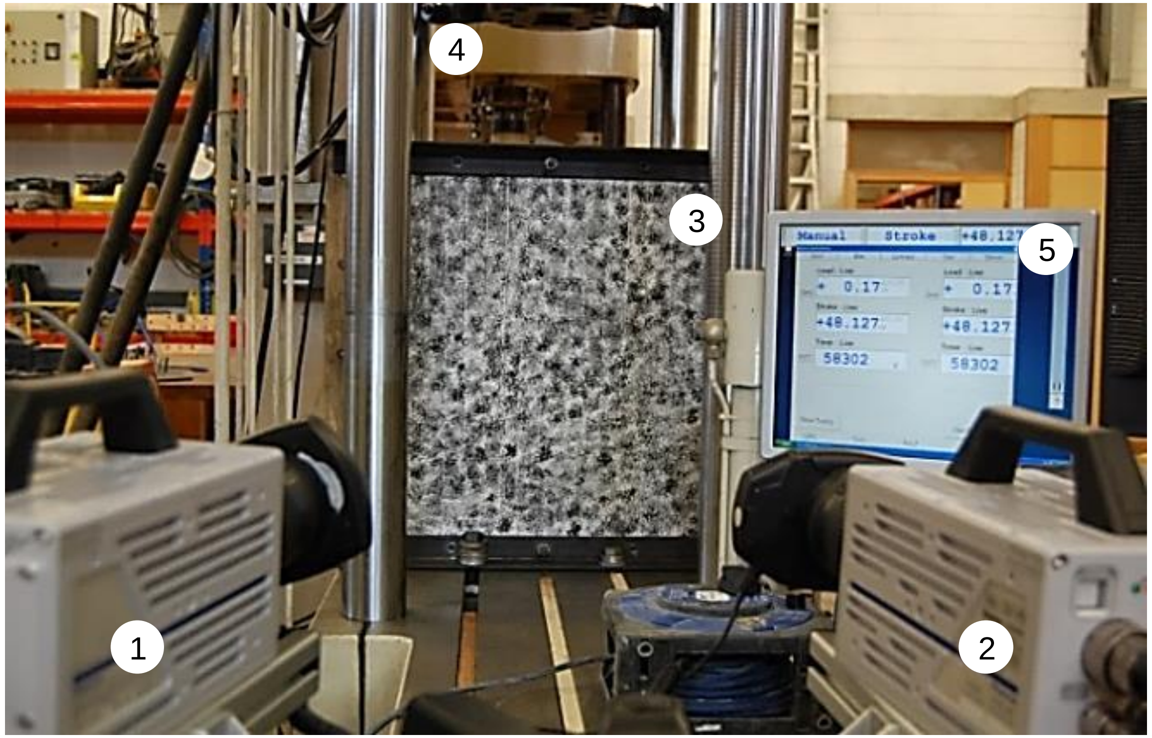
Hector F. Archila
hector.archila@bath.edu

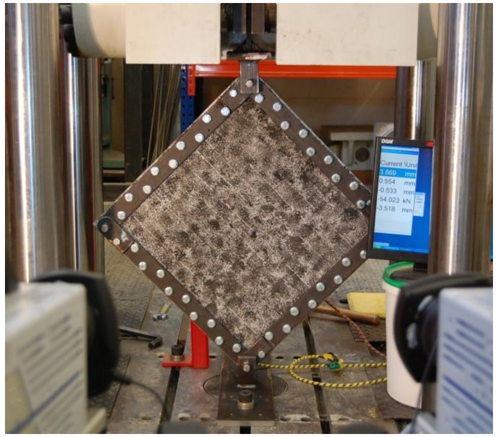
Testing of G-XLam panels

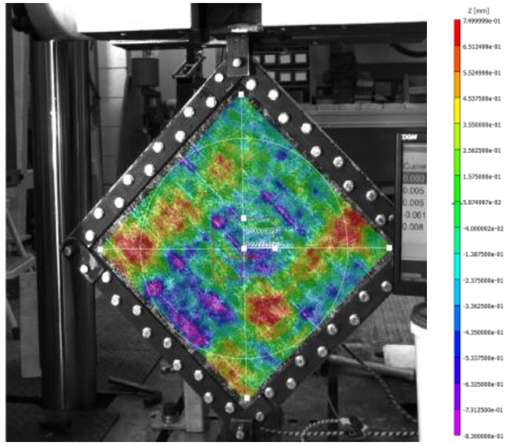
Elastic parameters MOE, G, V



1 & 2. High speed cameras; 3 G-XLam panel; 4. Test machine; 5. Monitor

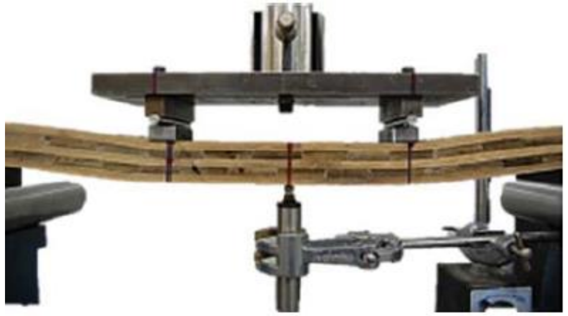
In-plane compression test using digital image correlation (DIC) (BS EN 789)





Picture frame panel shear test using DIC (ASTM E5 19-02)

- ✓ *600x600mm G-XLam3-5 panels*
- ✓ *Panels conditioned at 27±2° C and RH of 70±5% for 20 days (MC=12%).*
- ✓ *Load limited to elastic deformation.*
- ✓ *Rate 0.5mm/min (all tests)*
- ✓ *LVDT and virtual extensometers.*



Bending test (BS EN 789)

UNIVERSITY OF BATH
Amphibia Group
Hector F. Archila
hector.archila@bath.edu

Testing of G-XLam panels

Elastic parameters MOE, G and bending strength

	Birch plywood (8.5 to 25 mm)	CLT-3	CLT-5	G-XLam 3 (~ 17 mm) Mech. Test	G-XLam 5 (~ 27 mm) Mech. Test
$E_{L\ (0)}$	9.0 GPa	7.42 GPa	6.74 GPa	14.86 GPa	12.48 GPa
$E_{T\ (90)}$	7.9 GPa	3.91 GPa	4.62 GPa	7.43 GPa	8.74 GPa
$G_{v\ (xy)}$	-	0.65 GPa	-	0.67 GPa	0.72 GPa
$E_{m\ (bend)}$	9.7 GPa	11.6 GPa	-	**23.68 GPa**	**19.36 GPa**
$f_{m\ (bend)}$	-	-	-	99.92 GPa	91.76 GPa

✓ *CoV < 12% (coefficient of variation)*

Hector F. Archila
hector.archila@bath.edu

Engineered Bamboo

-for structural applications-

Source image: www.ecobuild.co.uk

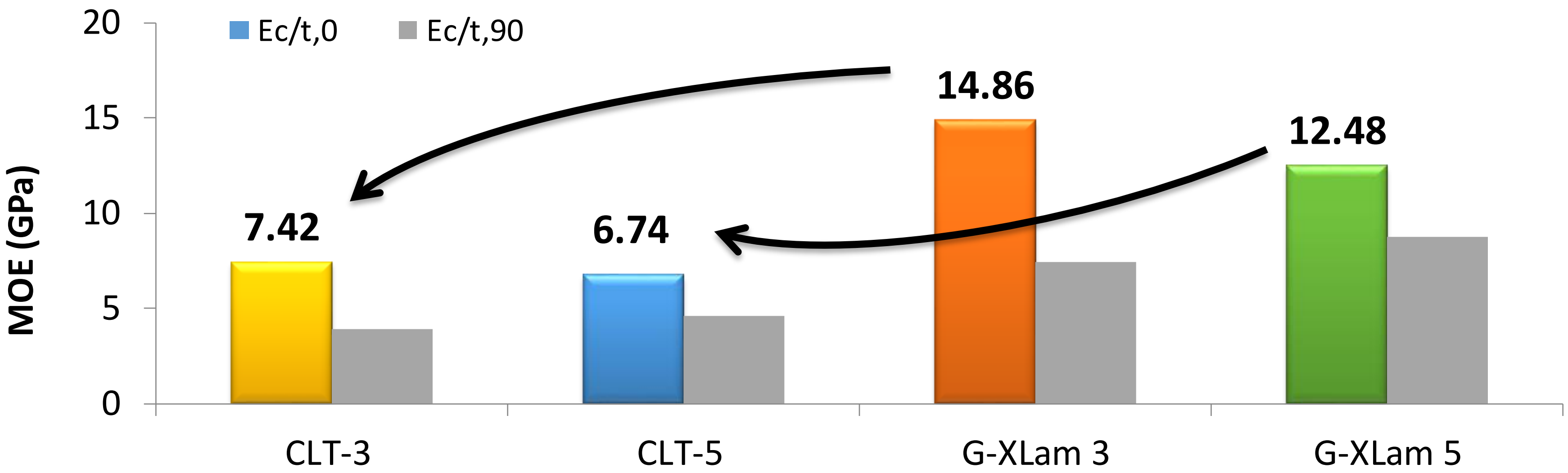
CLT panels

480 to 500 kg/m^3

G-XLam panels 2x MOE & Density

Improved Hardness & resistant to decay

890.9 kg/m^3



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hector.archila@bath.edu

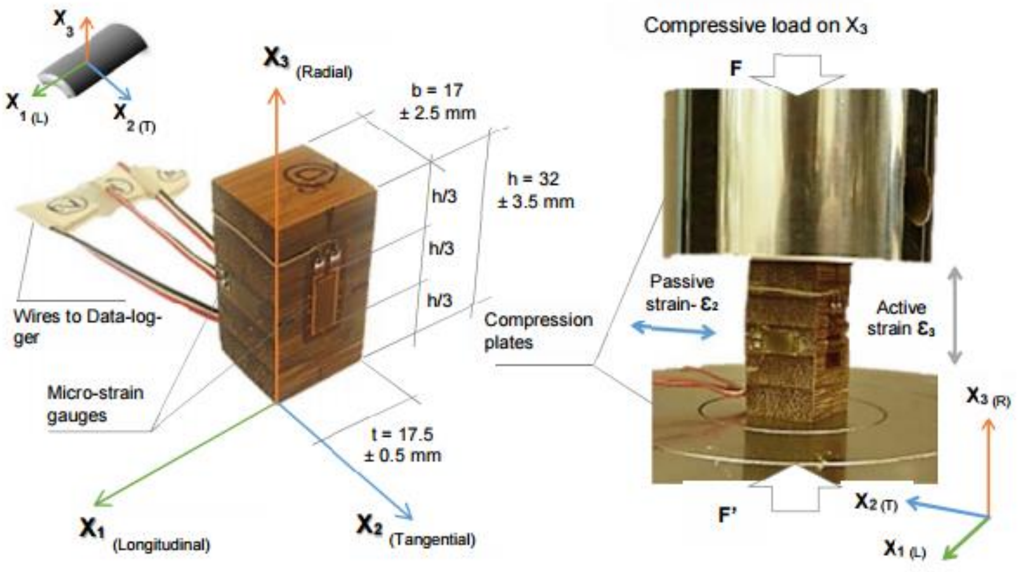


Figure 7-9. Typical specimen size and compression test set up for load applied along the radial direction.

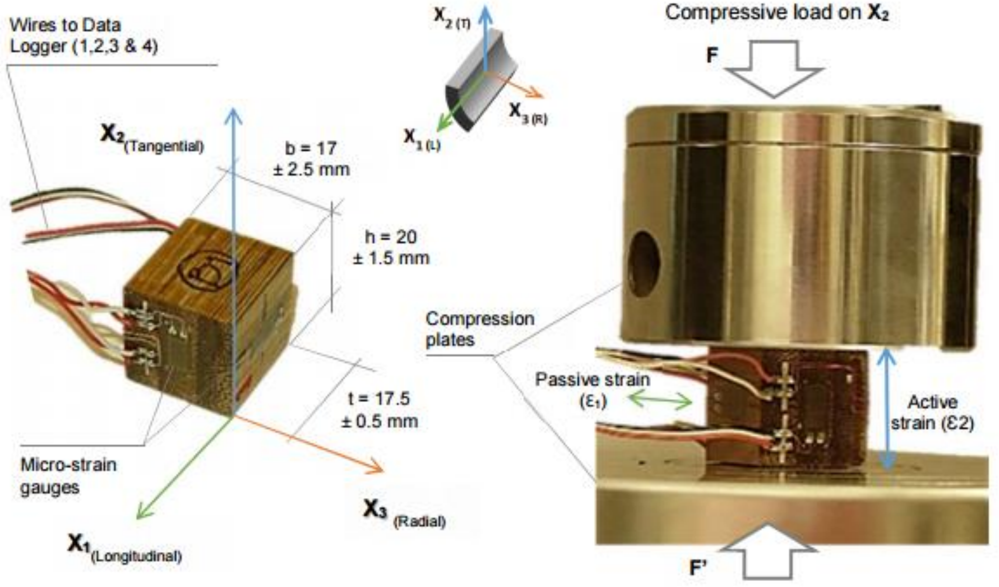


Figure 7-10. Typical specimen size and compression test set up for load applied along the tangential direction.

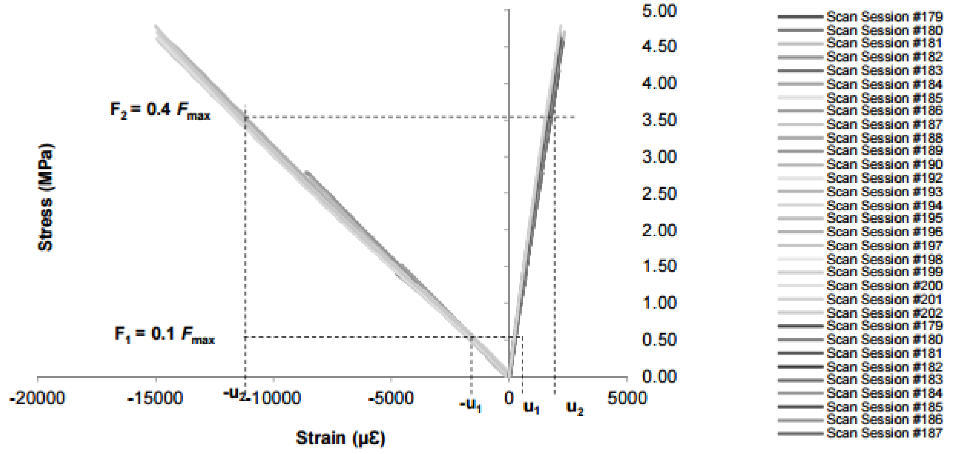


Figure 7-11. Typical strain-stress graph plotted from the results of a radial compression test on specimens of sample C (scan sessions represent the repetitions undertaken).

Elastic values and Poisson's ratios of samples A, B and C were calculated using the strain values $(u_2 - u_1)$ on the linear regression line between $0.1\boldsymbol{F}_{\max}$ and $0.4\boldsymbol{F}_{\max}$. Calculation of the compression modulus of elasticity $(\boldsymbol{E_c})$ followed the formula:

$$E_c = \frac{(F_2 - F_1)}{(u_2 - u_1) \cdot A} \qquad \text{7-4}$$

where
$(F_2 - F_1)$ is the increase of load between $0.1\boldsymbol{F}_{\max}$ and $0.4\boldsymbol{F}_{\max}$
and $(u_2 - u_1)$ is the increase of deformation corresponding to $(F_2 - F_1)$ using the linear regression line.

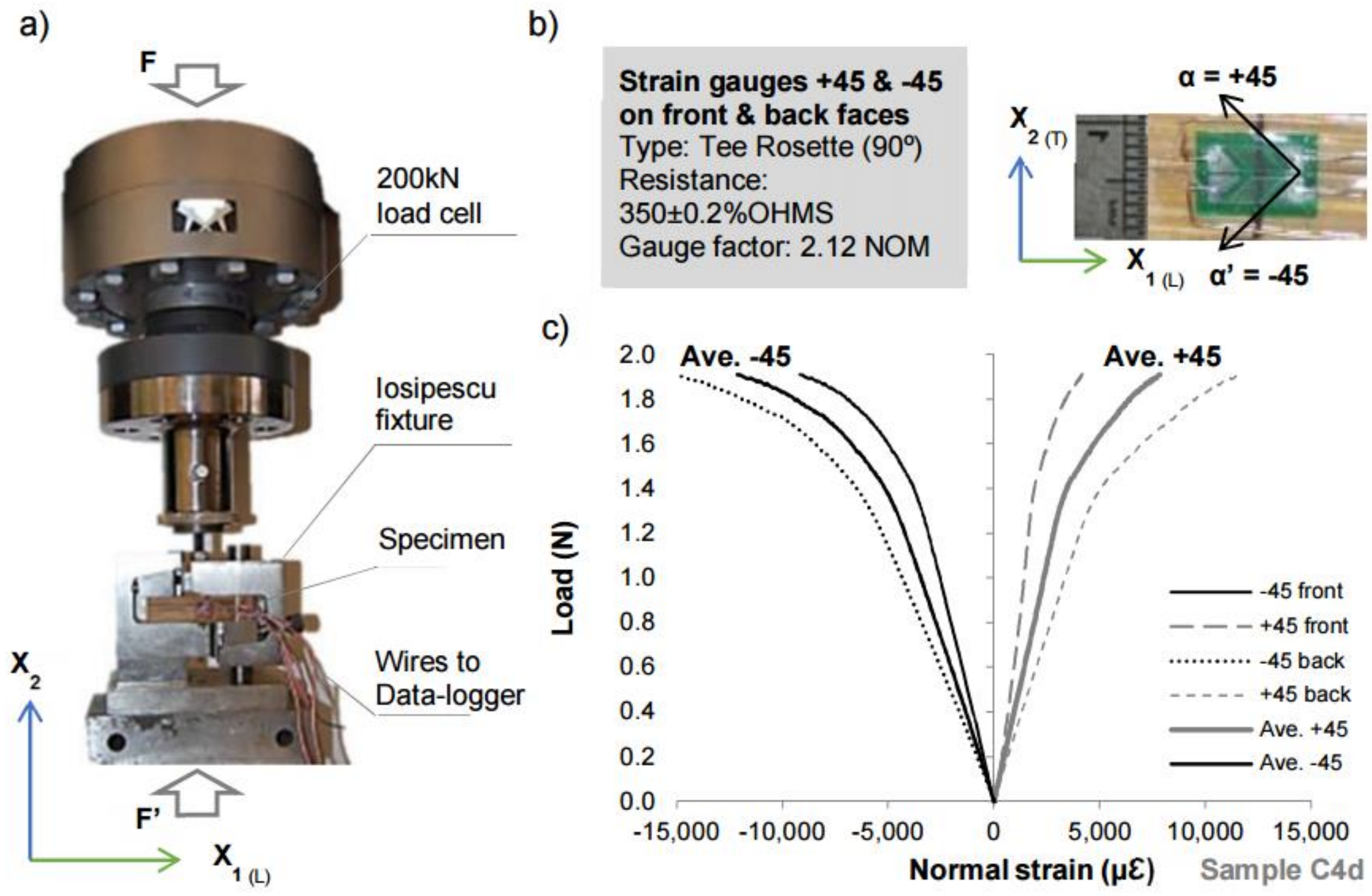
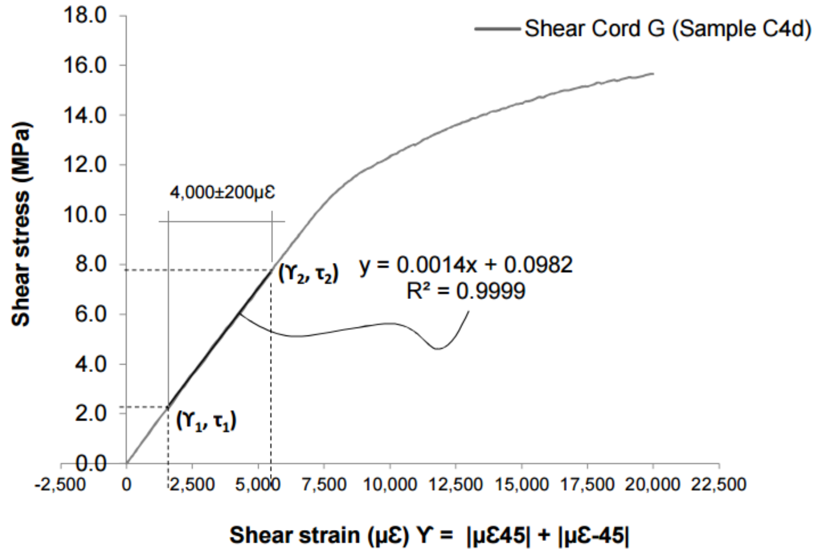


Figure 7-20. a) Iosipescu shear test set-up on INSTRON. b) Specifications of the strain gauge used. c) Typical load-strain graph for +45 and -45 strain gauges readings on front and back faces and their average for both orientations (+45 and -45).



The apparent shear modulus is then defined as the ratio of average shear stress to shear strain as expressed in Equation 7-5.

$$G_{12}^{app} = \frac{\tau^{av}}{\Upsilon^{av}} \qquad 7\text{-}5$$

And the ratio of the difference in applied shear stress and resulting shear strain ($\Delta\tau / \Delta\Upsilon$) is the shear chord modulus of elasticity (G^{chord}) as expressed in Equation 7-6.

$$G_{12}^{chord} = \frac{(\Delta\tau)}{(\Delta\Upsilon)} \qquad 7\text{-}6$$

where
$\Delta\tau$ is the difference of shear stress between τ_2 and τ_1
and $\Delta\Upsilon$ is the difference of shear strain between Υ_2 and Υ_1.

G-XLam3 and G-XLam5 panels with dimensions of 600x600mm and 700x700mm were subjected to mechanical testing. These sizes are considered to be representative volume elements (RVE) of potentially larger commercial size panels. The testing programme included in-plane compression tests in the X_1 (longitudinal) and X_2 (transverse) directions, four point bending test and in-plane shear test (Figure 10-1).

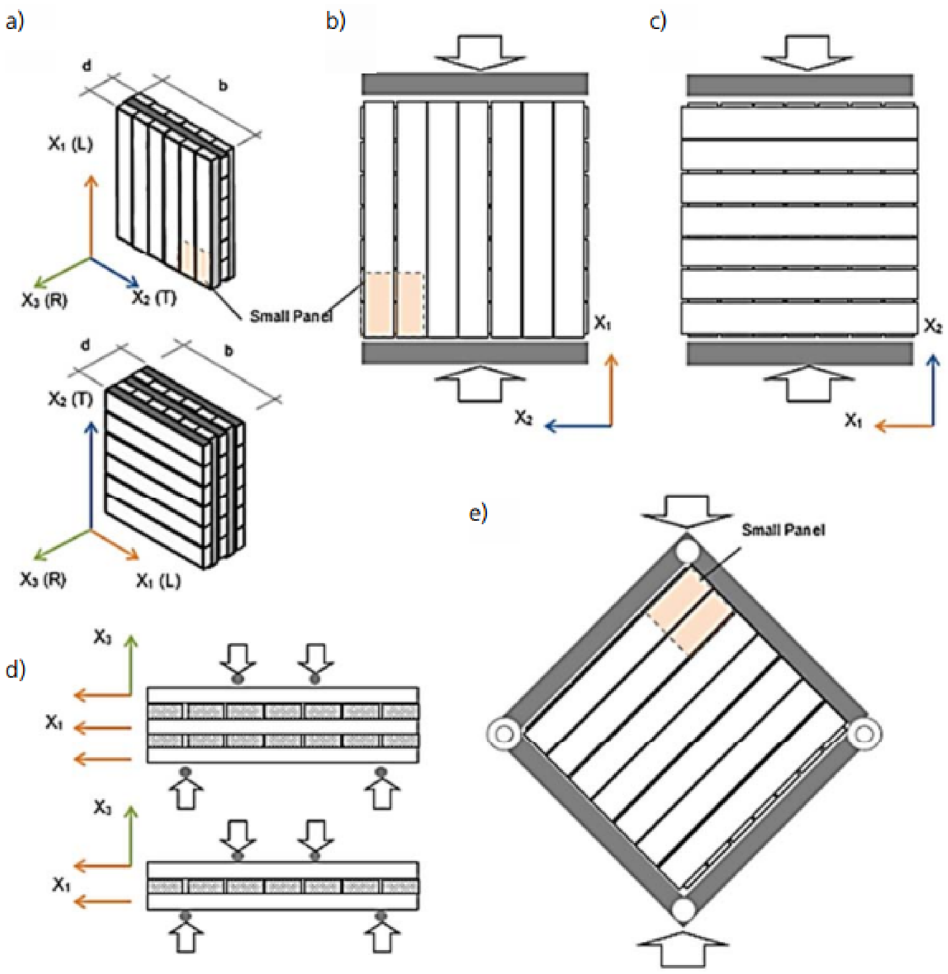


Figure 10-1. a) Geometric (X_1, X_2, X_3) axes of G-XLam3 and G-XLam5 panels. b) Diagram of the compression test in the longitudinal direction of the panel. c) Diagram of the compression test in the transverse direction of the panel. d) Diagram illustrating 4-point bending test setup for G-XLam3 and G-XLam5 panels. e) Diagram of the picture frame panel shear test.

Engineering strain ($\mathcal{E}$) was then calculated as the change in length ΔL per unit of original length L, as expressed in Equation 10-2.

$$\mathcal{E} = \frac{(\Delta \mathrm{L})}{(\mathrm{L})} = \frac{(l_1 - l_0)}{(l_0)} \qquad 10\text{-}2$$

where
l_0 is the initial length of the extensometer and l_1 its final length.

$$Ep_{c,0,90} = \frac{(F_2 - F_1)l}{(u_2 - u_1)A} \qquad 10\text{-}3$$

where

$F_2 - F_1$ is the increment of load between $0.1F_{max}$ and $0.4F_{max}$
$u_2 - u_1$ is the increment of engineering strain corresponding to $F_2 - F_1$
l is the gauge length (A-B length of the virtual extensometer), and
A is the cross sectional area of the panel.

$$\gamma_{xy} = \frac{\mathcal{E}x + \mathcal{E}y}{2}\left(\tan\theta' + \frac{1}{\tan\theta'}\right); \qquad \tau_{xy} = \frac{0.707\,P}{l\,t}; \qquad G_{xy} = \frac{\tau_{xy}}{\gamma_{xy}} \qquad 10\text{-}4$$

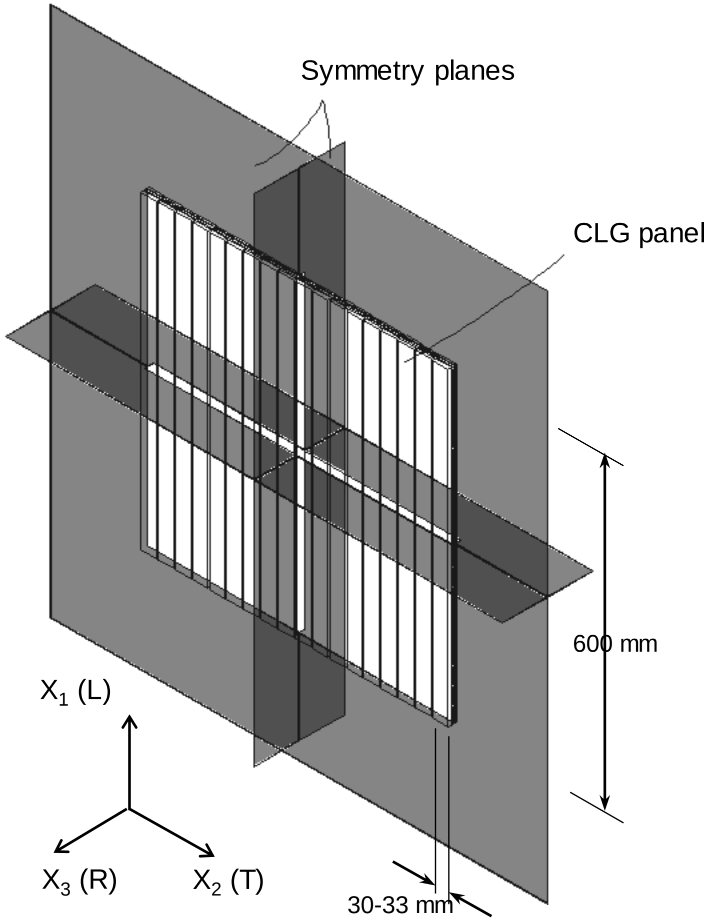
where
$\mathcal{E}x$ and $\mathcal{E}y$ are the measured strains in x and y
$\theta'$the resulting angle for $(dx_1,\ dy_1)$
P is the force applied, l the side-length of the specimen and t the thickness of the panel.

$$E \cdot I = \frac{23 \cdot L^3}{1296} \cdot \frac{\Delta F}{\Delta\delta_{centre}} \qquad Ep_{m,\ global} = \frac{23 \cdot L^3}{1296 \cdot I} \cdot \frac{(f_2 - f_1)}{(w_2 - w_1)} \qquad 10\text{-}5$$

where
$E \cdot I$ is the bending stiffness,
L is the span,
$f_2 - f_1$ is the increment of load between $0.1F_{max}$ and $0.4F_{max}$
$w_2 - w_1$ is the increment of deflection between $f_2 - f_1$ and
I is the moment of inertia or second moment of area of the beam section ($I = b \cdot d^3/12$).

Numerical and FE analysis

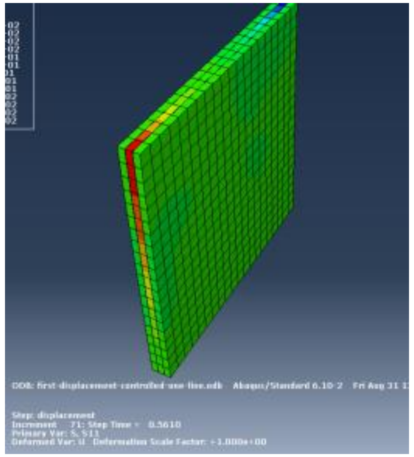
Prediction and simulation = Standardization

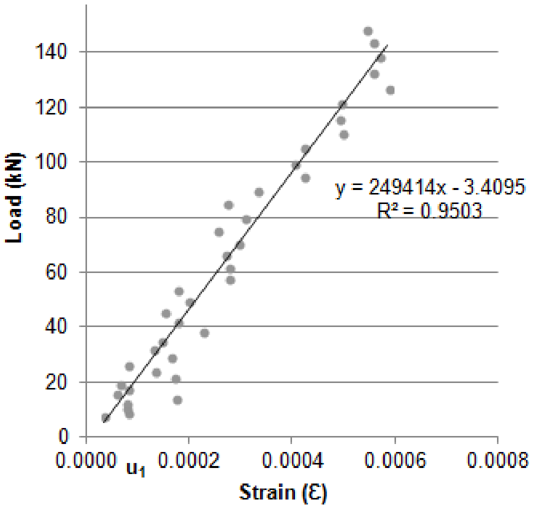


$$Ep_{t,c} = \frac{\sum_{i=1}^{n-1} E_{i\ t,c} \cdot h_i}{\sum_{i=1}^{n-1} h_i}$$

✓ *Analytical design methods for plywood and CLT panels*
BS EN 14272 (BSI 2011)

✓ *BS EN 789:2004 [8] standard for structural timber elements*





Materials & Features

	Round Bamboo	Strand Woven bamboo (SWB)	Cross-Lam Timber (CLT)	Steel	Engineered Bamboo Products
Labour	✗	✗	~	✗	✓
Stability	✗	✓	~	✓	✓
Temp. & Time	✓	✗ ~ 200°C / 2h	✓	✗ > 1,000°C /8-12h	✓ **~ 150°C / 15 min**
CO_2	✓	~ 0.14 ton CO_2/kg	~ 0.75 ton CO_2/m^3	✗ (-) 2 ton CO_2/kg	✓ **~ 1 ton CO_2/m^3**
Properties	✓	~	✓	✓	✓
Transport	✗	✓	~	✓	✓


Strand Woven Bamboo Flooring
Source BothBest Enterprise Co., Ltd



UNIVERSITY OF BATH
Amphibia Group
Hector F. Archila
hector.archila@bath.edu