# Material Characterisation for Engineered Bamboo Products

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| | |
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| Ian Nettleship, PhD | University of Pittsburgh, USA |
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| Michael Richard, PhD (Pitt) | SGH, Boston MA, USA |


# Engineered bamboo is a composite material

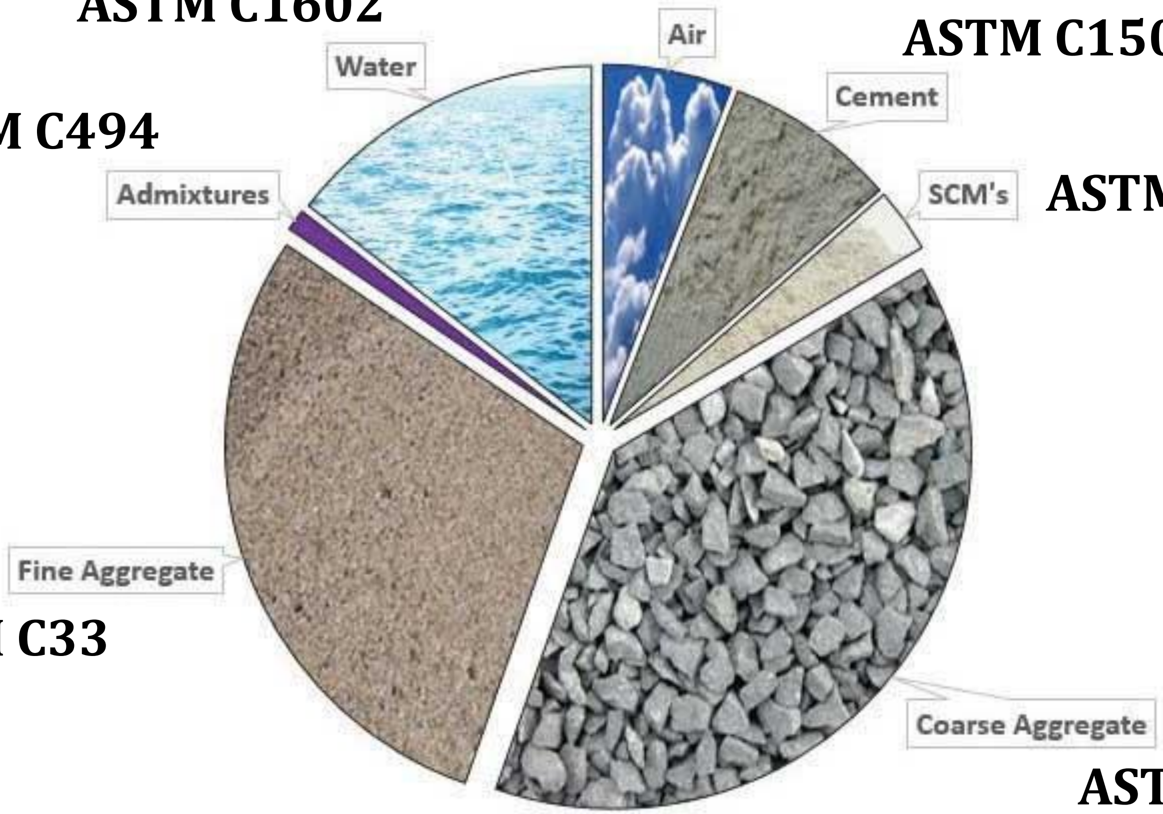
*just like concrete…*

**ASTM C1602**

**ASTM C494**

**ASTM C150**

**ASTM C1709**




**ASTM C33**

**ASTM C33**

exclusive of **properties** of concrete: **ASTM C31, C39, C496, etc.**

# Engineered bamboo is a composite material

Engineered bamboo is complicated by the facts that

a) the 'feedstock' comes in a variety of species, sizes, conditions

b) the 'feedstock' is highly variable in most every respect

Nevertheless, we have standard test methods available to ***quantify*** and ***grade*** feedstock properties:

ISO 22157:2019 and ISO 19624:2018

# ***Suite*** of ISO Bamboo Standards for Building Structures

1988 – proposed ***suite*** of materials and design standards for **full-culm** bamboo

1997 – initiation of standards development with support from Dutch government

2004 – ISO 22156:2004 – *Bamboo – Structural Design*

ISO 22157:2004 – *Bamboo – Determination of physical and mechanical properties*

intent signifying "version zero" documents

2013 – initiation of revision procedure

2018 – ISO 19624:2018 – *Bamboo* ***structures*** *– Grading of bamboo* ***culms***

2019 – ISO 22157:2019 – *Bamboo* ***structures*** *– Determination of physical and mechanical properties of bamboo* ***culms***

2021 – ISO 22156:2021 – *Bamboo* ***structures*** *– Bamboo* ***Culms*** *– Structural Design*

2023(?) - *Bamboo structures –* ***Engineered bamboo products*** *– Evaluation requirements*

2023(?) - *Bamboo structures —* ***Engineered bamboo products*** *– Test methods for determination of physical and mechanical properties*

# *Suite* of ISO Bamboo Standards - Grading

ISO 19624:**2018** – *Bamboo structures – Grading of bamboo culms*

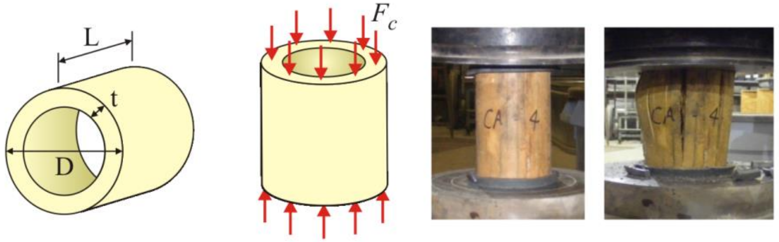
1. Scope
2. Normative references
3. Terms and definitions
4. Symbols and abbreviated terms
5. General
6. Visual Grading
7. Machine Grading
8. Structural properties of graded bamboo
9. Product identification
10. Documentation

Annex A: Example of application of clauses from ISO 19624 to a visual grading standard for bamboo culms based on external diameter and flexural properties

# *Suite* of ISO Bamboo Standards – Material Properties

ISO 22157:**2019** *Bamboo structures — Determination of physical and mechanical properties of bamboo culms*.

1. Scope
2. Normative references
3. Terms and definitions
4. Symbols and abbreviated terms
5. General requirements
6. Sampling and storage of specimens
7. Moisture content
8. Density
9. Mass per unit length
10. Compression strength parallel to the fibres
11. Tension strength parallel to the fibres
12. Bending strength parallel to the fibres
13. Shear strength parallel to fibres
14. Tension strength perpendicular to the fibres
15. Bending strength perpendicular to the fibres

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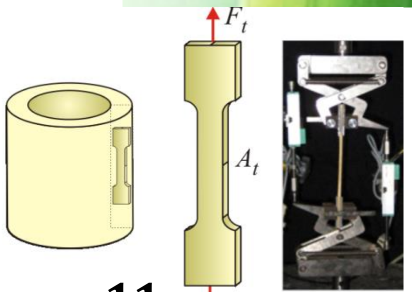


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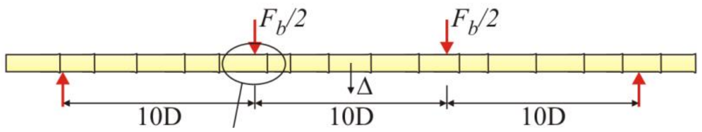


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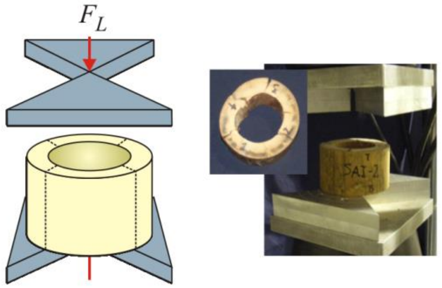


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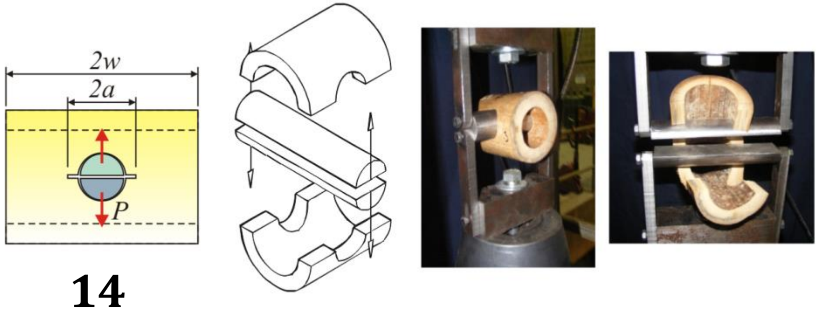
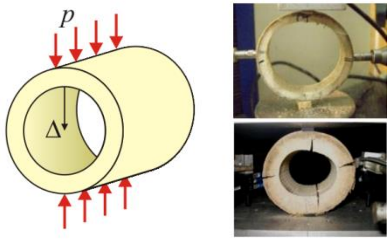
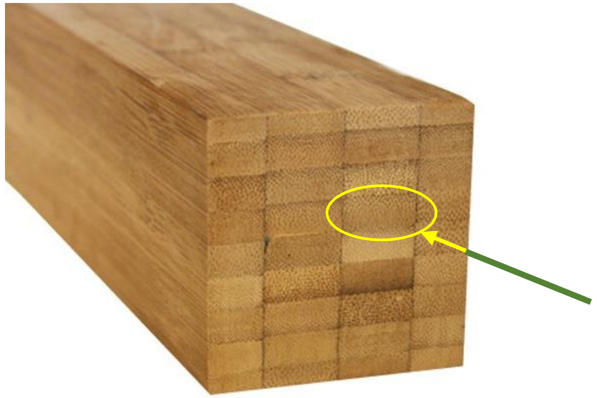



**14**




**15**

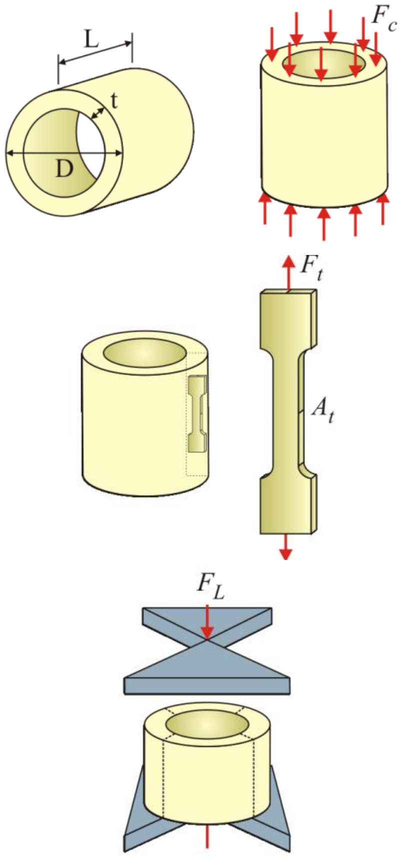
# Engineered bamboo is a composite material



**ISO 22157**

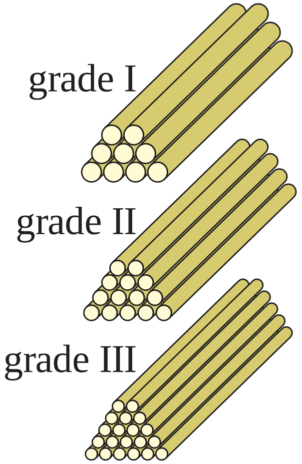
Moisture content

Density

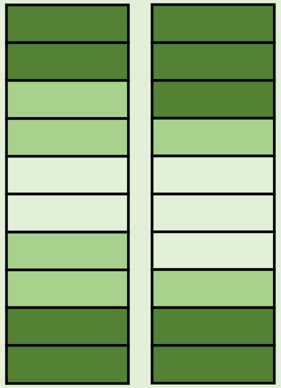



**ISO 19624**

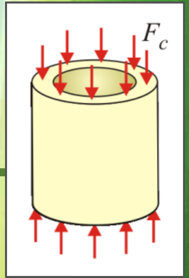
Grading

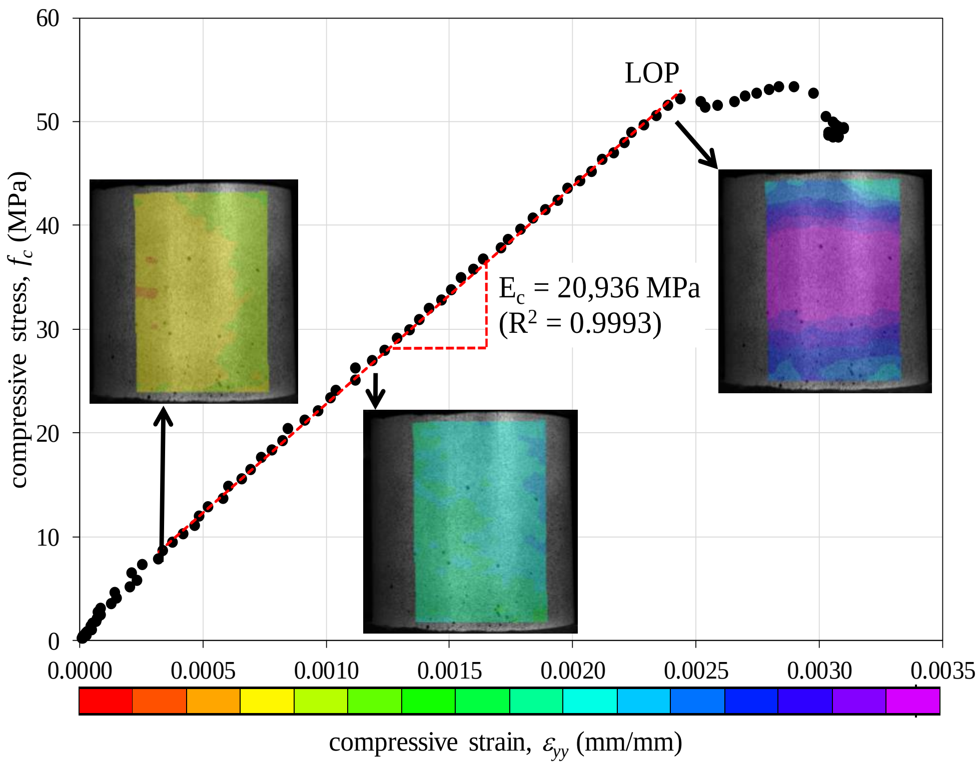


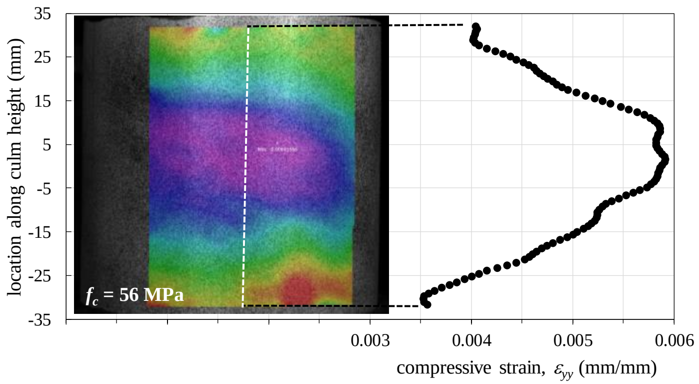

engineered layups

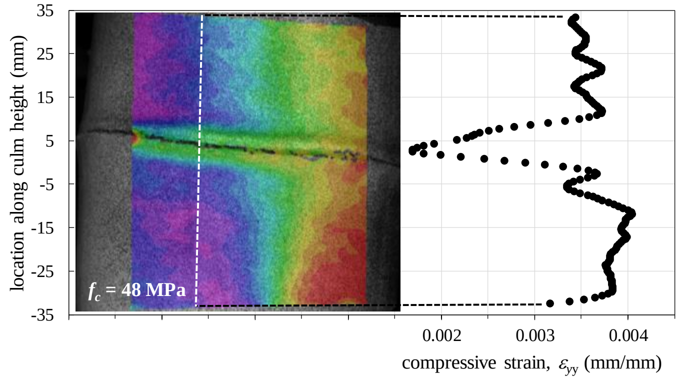


# ISO 22157 Compression



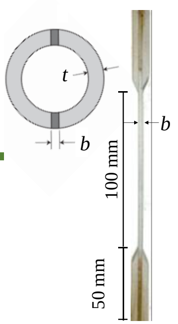

| | Internode specimen | | | Specimen with node | | | $p$-value | All specimens | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | n | average | COV | n | average | COV | | n | average | COV |
| $f_c$, MPa | 41 | 57.5 | 0.09 | 14 | 59.5 | 0.06 | 0.19 | 55 | 57.9 | 0.08 |
| $E_c$, MPa | | 20,300 | 0.10 | | 20,640 | 0.12 | 0.61 | | 20,380 | 0.10 |
| LOP, MPa | | 50.9<br>$0.89f_c$ | 0.10 | | 50.7<br>$0.85f_c$ | 0.10 | 0.90 | | 50.7<br>$0.88f_c$ | 0.10 |

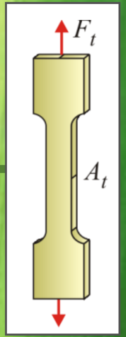
Test method is:

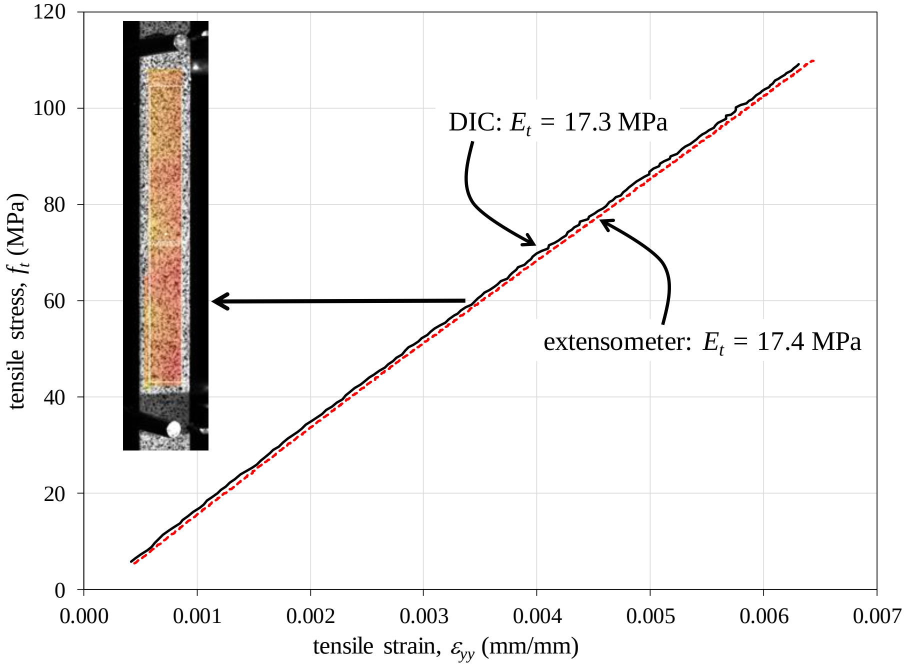
- well-established
- easily conducted
- consistent (low COV)
- insensitive to presence of node

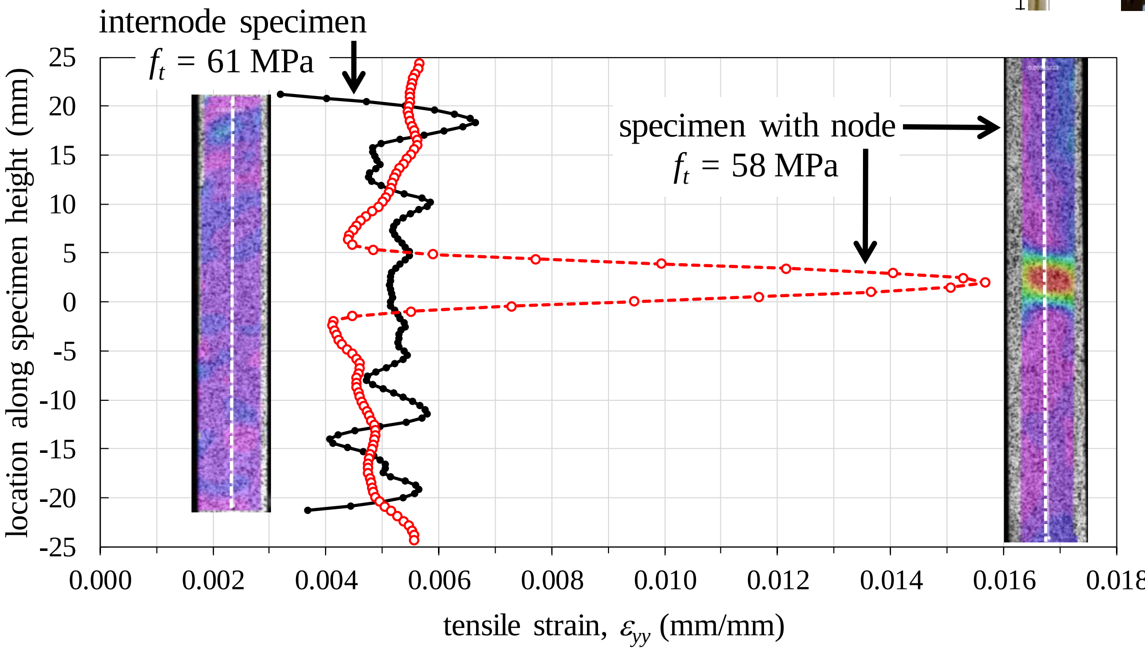

Gauss, C., Savastano, H. and Harries, K.A. (2019) Use of ISO 22157 Mechanical Test Methods and the Characterisation of Brazilian P. edulis bamboo. *Construction and Building Materials*, **228**. https://doi.org/10.1016/j.conbuildmat.2019.116728

# ISO 22157 Tension




| | Internode specimen | | | Specimen with node | | | $p$-value |
|---|---|---|---|---|---|---|---|
| | n | average | COV | n | average | COV | |
| $f_t$, MPa | 57 | 275 | 0.11 | 27 | 100 | 0.20 | 0.0001 |
| $E_t$, MPa | | 17,470 | 0.09 | | 11,190 | 0.18 | 0.0001 |

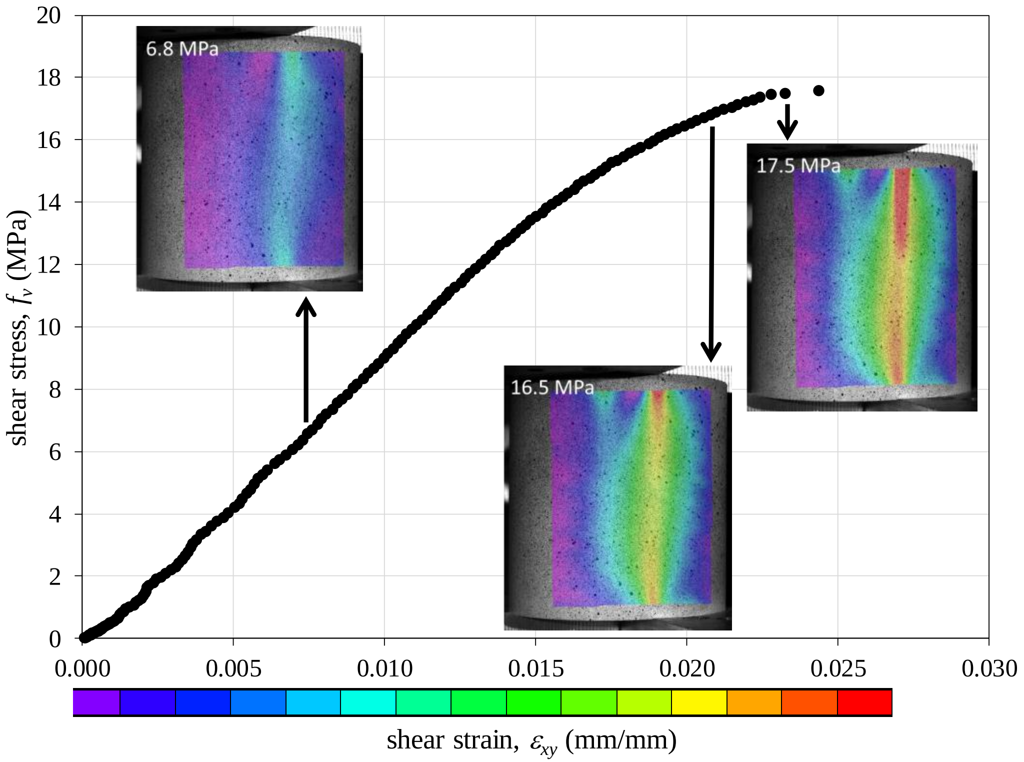
Test method is well-established

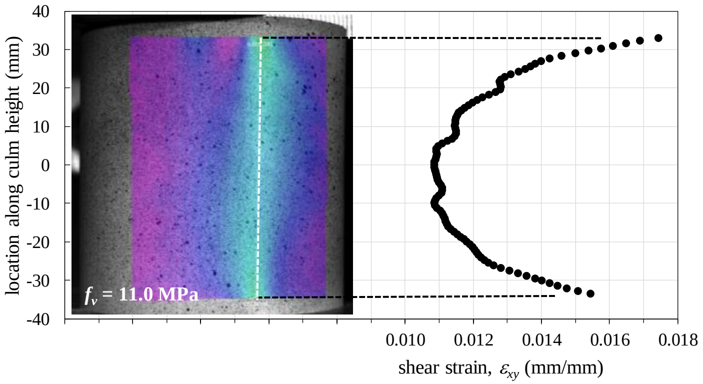
Results affected by:

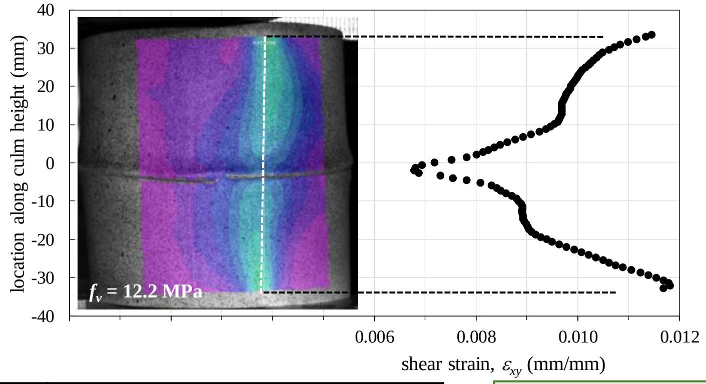
- presence of node
- method of gripping coupon
- boundary conditions of test frame

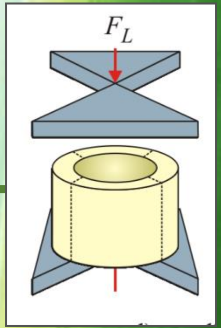

Gauss, C., Savastano, H. and Harries, K.A. (2019) Use of ISO 22157 Mechanical Test Methods and the Characterisation of Brazilian P. edulis bamboo. *Construction and Building Materials*, **228**, https://doi.org/10.1016/j.conbuildmat.2019.116728

# ISO 22157 [Bowtie] Shear




| | Internode specimen | | | Specimen with node | | | *p*-value | All specimens | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | n | average | COV | n | average | COV | | n | average | COV |
| $f_v$, MPa | 36 | 18.0 | 0.08 | 13 | 18.1 | 0.07 | 0.83 | 49 | 18.1 | 0.08 |
| *G*, MPa | | 2850 | 0.10 | | 2790 | 0.10 | 0.52 | | 2830 | 0.10 |
| LOP, MPa | | 12.2<br>0.68$f_v$ | 0.09 | | 12.2<br>0.67$f_v$ | 0.10 | 1.00 | | 12.2<br>0.67$f_v$ | 0.10 |

Test method is:

- easily conducted
- consistent (low COV)
- insensitive to presence of node
- limited applicability

Gauss, C., Savastano, H. and Harries, K.A. (2019) Use of ISO 22157 Mechanical Test Methods and the Characterisation of Brazilian P. edulis bamboo. *Construction and Building Materials*, **228**, https://doi.org/10.1016/j.conbuildmat.2019.116728

# Perhaps a single test?

## Concrete

All materials parameters can be reliably established from a single test method

$\rightarrow$ $\boldsymbol{f_c'}$ $\rightarrow$

$$f_t = 0.17\sqrt{f_c'}$$

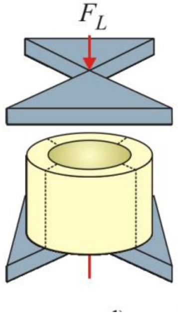
$$f_r = 0.50\sqrt{f_c'}$$

$$E = 4750\sqrt{f_c'}$$

## Bamboo

Like wood, most properties are a function of ***density***

Some preliminary study favours the bowtie shear test as a ***representative test method*** from which other properties relevant to full-culm construction may be inferred




$\rightarrow$ $\boldsymbol{\tau_{II}^*}$ $\rightarrow$

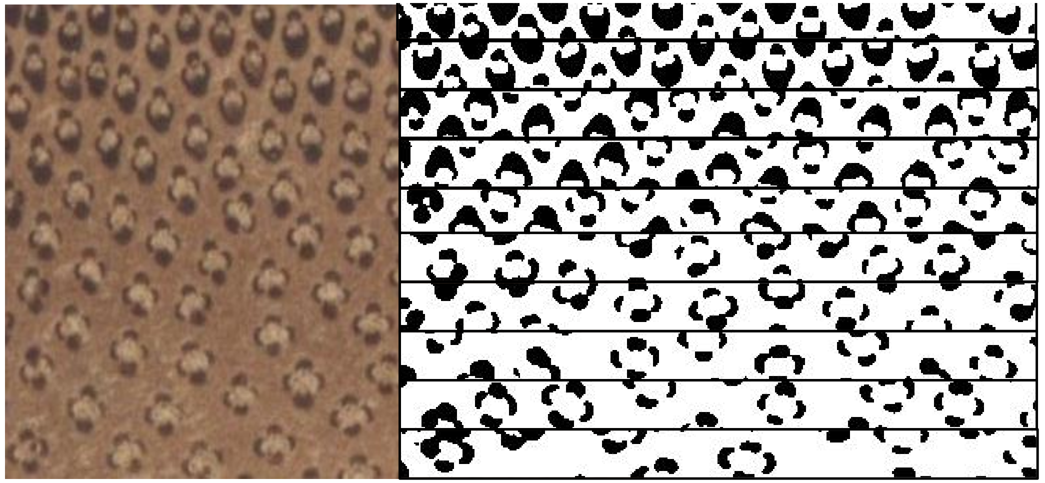
$$\tau_I^* = 0.17\,\tau_{II}^*$$

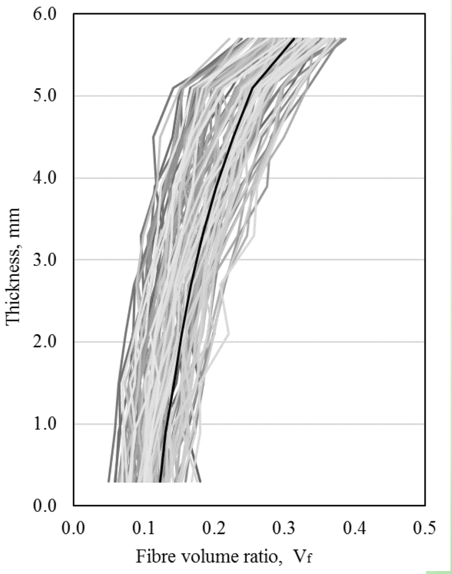
$$\left(\frac{\tau_I}{\tau_I^*}\right)^m + \left(\frac{\tau_{II}}{\tau_{II}^*}\right)^n = 1$$


Richard, M., Gottron, J., Harries, K.A. and Ghavami. K. (2017) Experimental Evaluation of Longitudinal Splitting of Bamboo Flexural Components, *ICE Structures and Buildings* Themed issue on bamboo in structures and buildings, **170**(4), *265-274* http://dx.doi.org/10.1680/jstbu.16.00072

# Glue-laminated fabrication

**Determination of fibre volume content** using imaging methods






typical strip

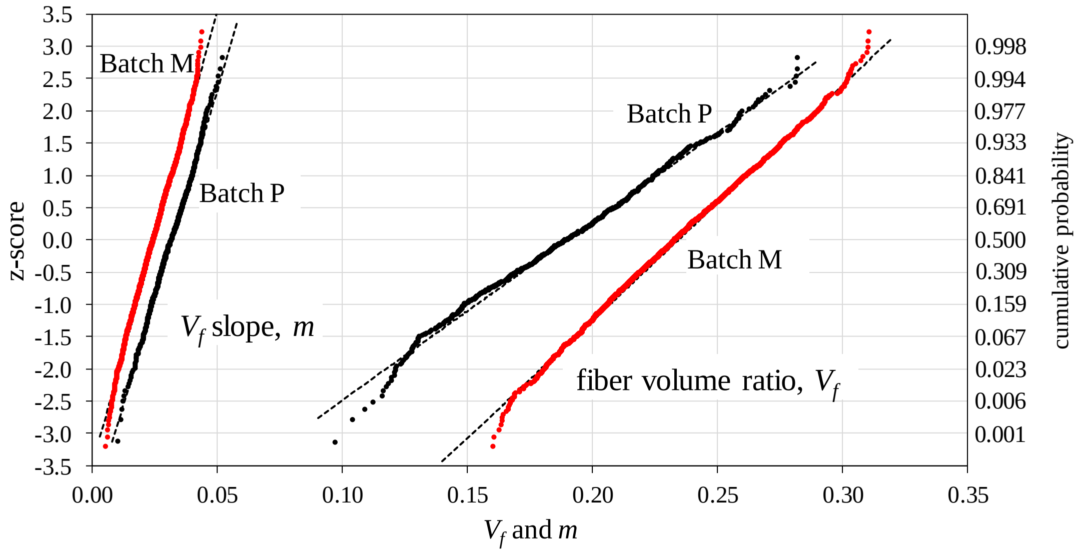
nodal region
at section

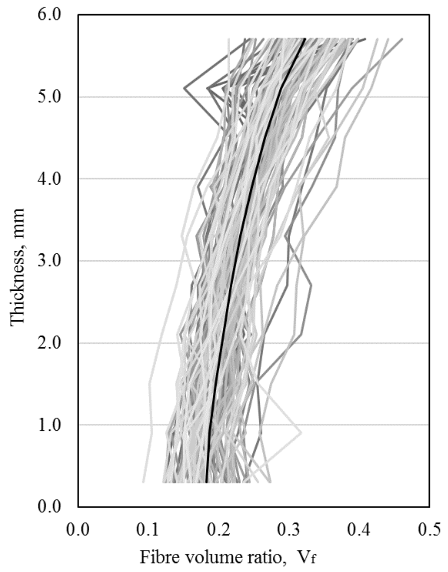
*NB: the crack seen in the section is from a flexural test of this beam and is of no concern in the context of this presentation*

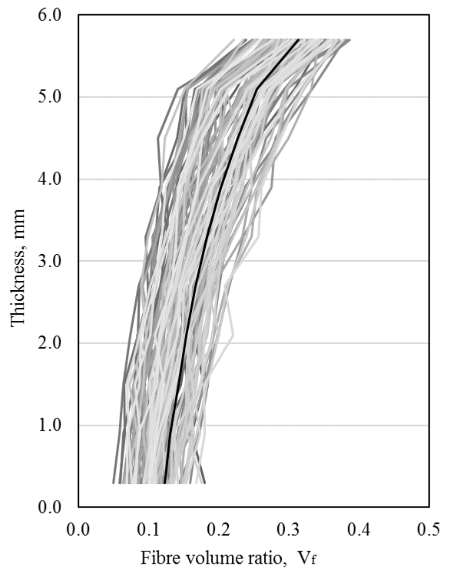
Akinbade, Y., Harries, K.A., Sharma, B., Nettleship, I. and Ramage, M. (2020) Variation of through-culm wall morphology in *P. edulis* bamboo strips used in glue-laminated bamboo beams, *Construction and Building Materials*, **232**, https://doi.org/10.1016/j.conbuildmat.2019.117248

# Glue-laminated fabrication

| Batch | **M** | **P** |
|---|---|---|
| beam dimension (mm) | 140 x 90 | 120 x 60 |
| number of beams | 38 | 20 |
| 19 x 6 mm *P. edulis* (Moso) strips in beam | 64 or 78 | 48 or 54 |
| Strip images extracted | 2590 | 927 |
| Strip images analyzed | 2309 (89%) | 601 (66%) |
| near-node strips | 80 (3.1%) | 37 (4.1%) |
| fibre volume ratio, $V_f$ | **0.234** (0.12) | **0.190** (0.19) |



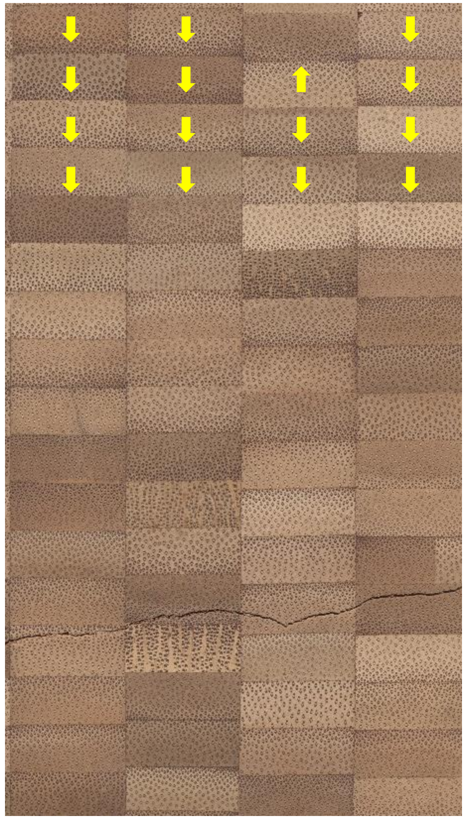



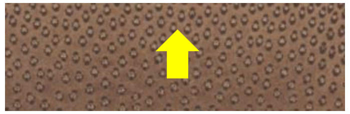



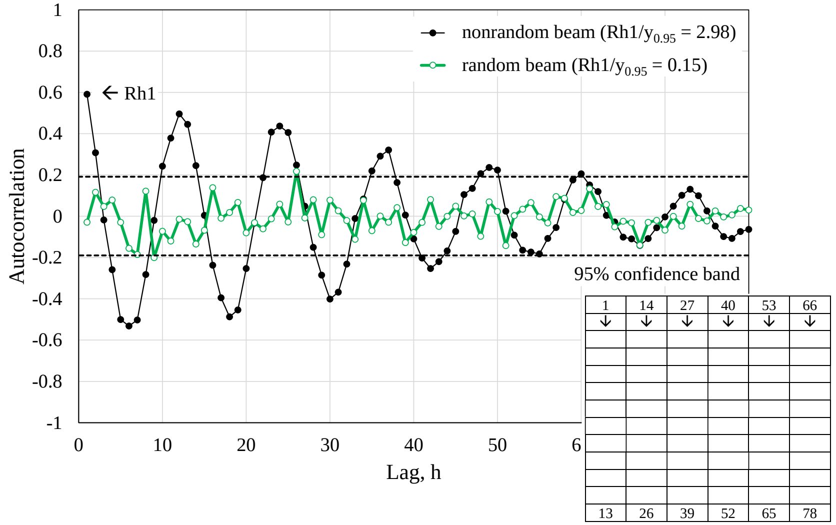

Akinbade, Y., Harries, K.A., Sharma, B., Nettleship, I. and Ramage, M. (2020) Variation of through-culm wall morphology in *P. edulis* bamboo strips used in glue-laminated bamboo beams, *Construction and Building Materials*, **232**, https://doi.org/10.1016/j.conbuildmat.2019.117248

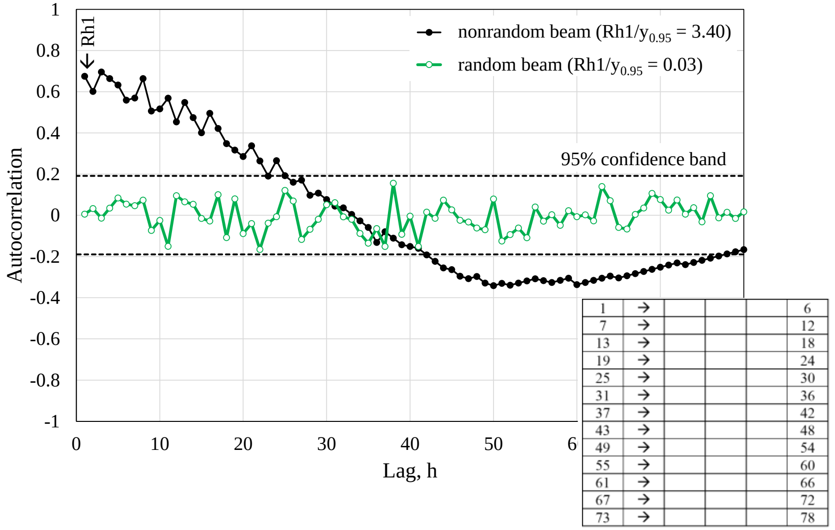
# Glue-laminated fabrication

## Orientation of strips







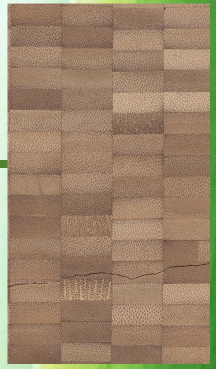

Using autocorrelation analysis:

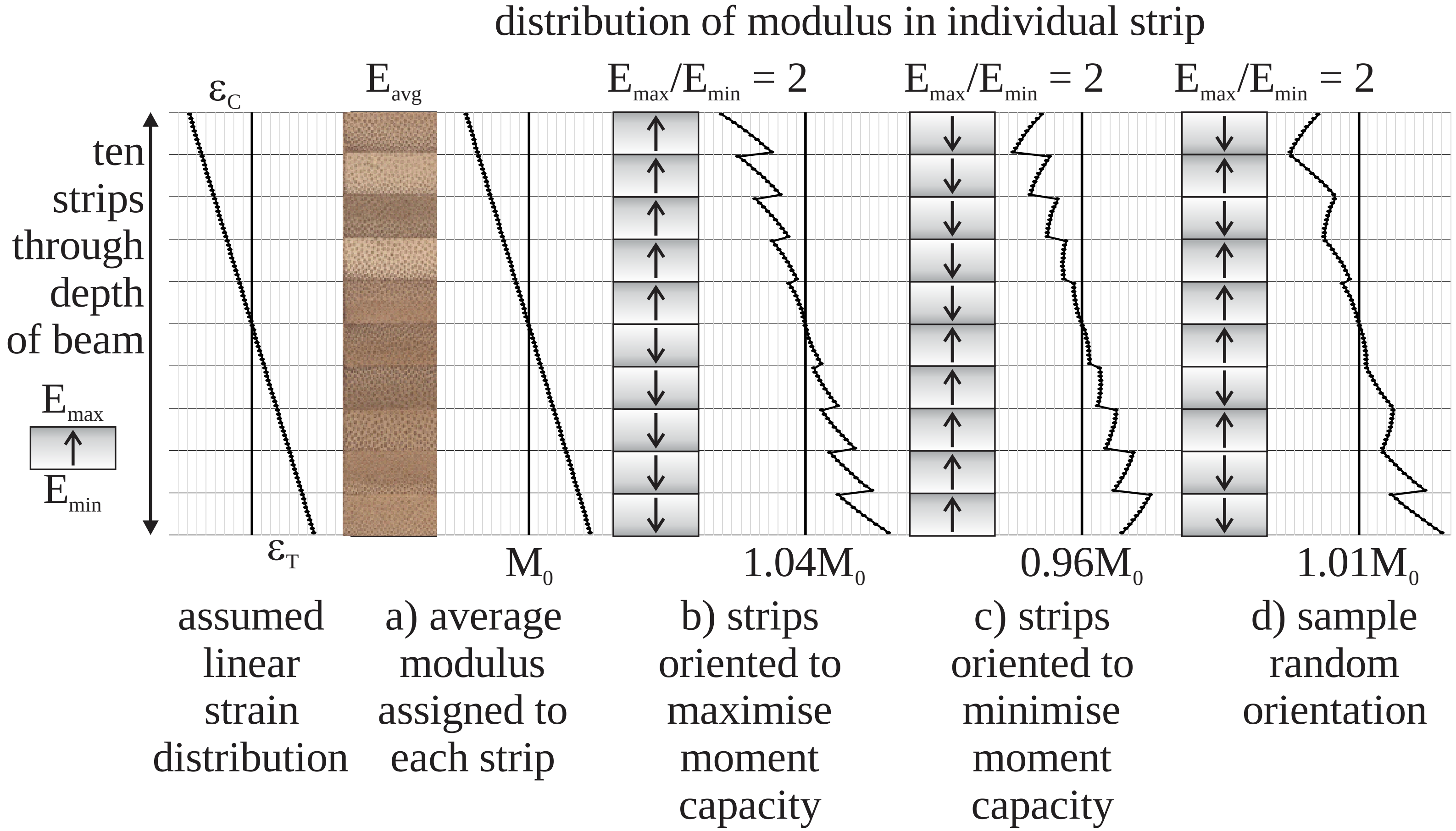
- Most beams indicate "random" distribution of strip orientation ($Rh1/y_{0.95} < 1$)
- "cyclic" results in vertical direction show effect of fabrication (strips → boards → beam member)
- strongly autoregressive behaviour in horizontal direction.
- The apparently non-random distribution is an artefact of the laminated bamboo beam production process.

Akinbade, Y., Harries, K.A., Sharma, B., Nettleship, I. and Ramage, M. (2020) Variation of through-culm wall morphology in *P. edulis* bamboo strips used in glue-laminated bamboo beams, *Construction and Building Materials*, **232**, https://doi.org/10.1016/j.conbuildmat.2019.117248

# Glue-laminated fabrication

**Thought Experiment:** *What is the effect of strip orientation on flexural stress distribution of glue-laminated beam?*





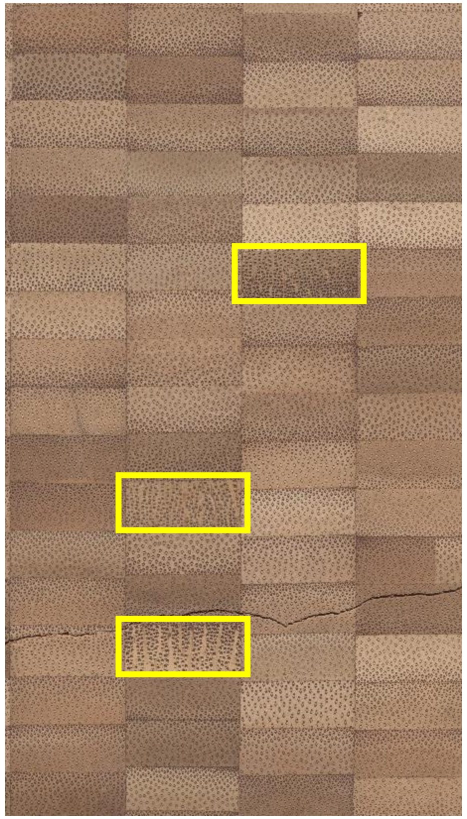

Although these effects are minor, they will impact reliability analyses.

The corollary of this is that these effects can be leveraged to produce a higher quality product

Akinbade, Y., Harries, K.A., Sharma, B., Nettleship, I. and Ramage, M. (2020) Variation of through-culm wall morphology in *P. edulis* bamboo strips used in glue-laminated bamboo beams, *Construction and Building Materials*, **232**, https://doi.org/10.1016/j.conbuildmat.2019.117248

# Glue-laminated fabrication

## Impact of Nodal Regions



Nodal regions are observed at a rate of about 3-5% - three are shown in this beam having 68 strips (4.4%).

They were observed to have been essentially randomly distributed.

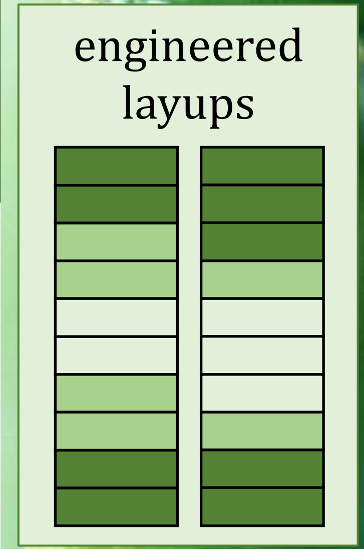
If the nodal region is about 10 mm long, we can infer that the node spacing for the bamboo feedstock in this study was 200-300 mm.

Presence of nodes affect ***tension*** capacity is therefore a factor in reliability assessment (determination of appropriate phi factors)

Random distribution is affected by fabrication process. A process can be envisioned in which nodes are not staggered lengthwise along the member.

Variation in feedstock nodal spacing may impact calculated reliability and therefore must also be accounted for in this calibration.

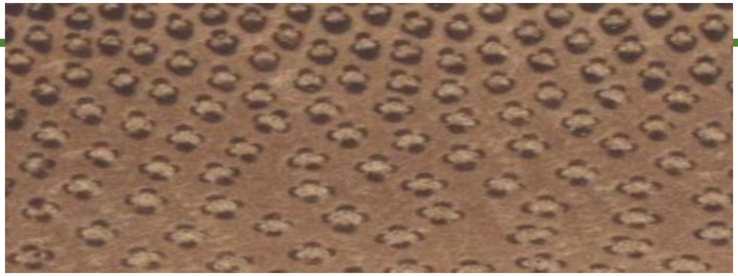
Raising the potential for engineered layups




Akinbade, Y., Harries, K.A., Sharma, B., Nettleship, I. and Ramage, M. (2020) Variation of through-culm wall morphology in *P. edulis* bamboo strips used in glue-laminated bamboo beams, *Construction and Building Materials*, **232**, https://doi.org/10.1016/j.conbuildmat.2019.117248

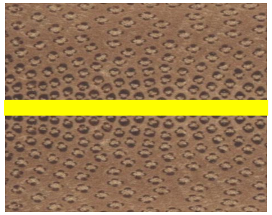
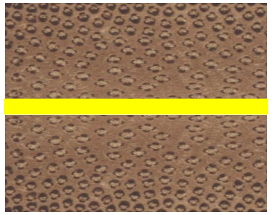
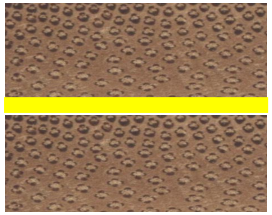
# One last concern…

**hydrophobic**



**hydrophilic**

## Performance of gluelines

| | Orientation | Bond Capacity |
|---|---|---|
|  | Outer-to-outer | 3.23 MPa |
|  | Inner-to-inner | 2.07 MPa |
|  | Outer-to-inner | not reported |

This is an issue that

- is unique to bamboo
- may impact adhesive selection
- may require a degree of standardization

Hydrophobicity/philicity may also affects resin performance of scrimber

Li, Cheng, Walinder and Zhou (2015) Wettability of oil heat-treated bamboo and bonding strength of laminated bamboo board, *Industrial Crops and Products* **69** 15-20

# Conclusions

Standardisation and quantification of bamboo 'feedstock' for engineered bamboo products:

- Is easily facilitated using existing standards (ISO 22157)
- Allows formalised grading protocols to be developed (ISO 19624)
- May permit development of engineered layups
- Is perhaps simpler than that required for full-culm applications (fewer tests)

Standards for fabrication are being developed and should address:

- Effects of random (or not) distribution of material flaws
- Permit graded products and enhanced reliability

*How does the inherent graded nature of bamboo affect the composite (glueline) behaviour of engineered bamboo?*

# Material Characterisation for Engineered Bamboo Products

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7, 9, 14, 16, 21 & 28 June 2022 at 1200 UCT