Research Article

Alfonso Cruz* and Caori Takeuchi

Optimizing bending strength of laminated bamboo using confined bamboo with softwoods

Abstract: The objective of the study was to improve the stiffness and bending strength of laminated bamboo through confinement with softwood. A total of 144 beams were tested, divided into 6 groups of 24 specimens each. The tests were conducted on specimens of laminated bamboo, wood, and composite sections with different levels of confined bamboo laminate (20, 40, 60, and 80%). The results indicated that the composite exhibited optimal behavior when the ratio of bamboo to wood was between 46 and 54%. Furthermore, the composite demonstrated a bending modulus of elasticity that was 16.6% higher and a modulus of rupture that was 18.3% higher than the values predicted by the mixing rule. A mathematical model was developed to predict the design mechanical properties based on composite thickness. This model was validated through 18 additional bending tests. This new material is an environmentally sustainable alternative that has the potential to be used as beams in buildings, providing improved mechanical performance, reduced weight, and lower manufacturing cost compared to bamboo laminates.

Keywords: wood, bamboo, composite material, modulus of elasticity, strain, stress, confined materials

1 Introduction

Wood and bamboo laminates have been shown to exhibit lower coefficients of variation in their mechanical properties compared to natural materials, such as raw bamboo and sawn timber [1–3]. Laminated materials have several advantages, such as larger cross-sections, defect elimination, and increased homogeneity [4–7]. In addition, vertical wood laminates offer a technical advantage by distributing the strength of external fibers among all the constituent elements [8].

To determine the mechanical properties of composite materials, the mixing rule is a commonly used method [2]. However, this methodology may not be suitable for materials with significant differences between constituent materials, as observed in the case of confined concrete [9,10], wood tubes reinforced and confined with fibers [11,12], or the confinement effectiveness of bamboo scrimber-filled steel tube [13,14]. Therefore, a deeper understanding of the mechanical behavior, loading conditions, distribution, size, and orientation of reinforcing fibers is necessary for composite materials [15].

Despite numerous studies on the structural use of wood and bamboo in construction [16–19], limited research has been conducted on the use of confined bamboo [11,20,21]. A preliminary study on compression tests parallel to the grain of confined bamboo laminates with softwoods with a bamboo thickness of 19.48% presented a 45% increase in stiffness and a 4% increase in resistance [20]. Conversely, inverting the materials resulted in stiffness and strength values lower than those predicted theoretically [22].

Bamboo scrimber and laminates under flexural loading commonly fail due to shear failure parallel to the grain [23,24]. The maximum bending stress of bamboo laminates for short beams was found to be approximately 50% lower than that in long beam tests [25], indicating that low parallel shear strength affects bending performance [26]. Therefore, research has been conducted with glass fibers [27] and carbon fibers [28,29] to enhance the performance of laminated bamboo beams. A study on the bending of confined bamboo laminates with softwoods found that the resistance of a bamboo laminate could be matched by a composite of equivalent dimensions using only 36.89% bamboo [30], resulting in optimal synergy [31].

The use of materials from reforestation processes in construction offers numerous technical advantages, including lower weight, reduced seismic risk, and reduced load on foundations [24]. Softwoods and bamboo from reforestation processes have a positive environmental impact by capturing greenhouse gases, generating no waste, and providing an

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unlimited resource as they are materials of the circular economy [24,32].

2 Materials and methods

The purpose of this research was to improve the mechanical characteristics of bamboo laminates under bending through confinement with softwoods. These composite laminates consisted of a central layer of Guadua angustifolia Kunth bamboo laminated with horizontal fibers and two layers of softwood surrounding it (as illustrated in Figure 1).

The wood and bamboo used in the experimental tests were sourced from areas that had undergone reforestation to compensate for the biomass extracted from them. These reforestation efforts were carried out by accredited companies in Colombia (Table 1).

In Colombia, bamboo strips are available in commercial sizes of up to 2.70 m, as they are used for manufacturing bamboo laminate panels of size 1.20 m × 2.60 m. In contrast, wood planks were obtained with dimensions of 4 m in length, 8 inches in width, and 1 inch in thickness. To ensure proper bonding of the components, both the wood planks and bamboo strips were brushed on all their faces. The laminates were then arranged in their final configuration, glued, and compressed for 24 h at a constant pressure of 0.8 MPa and room temperature (20°C). A 400 g/m² adhesive was applied to all surfaces in contact with each other, with a composition of 80% adhesive and 20% catalyst. A metal frame and a hydraulic press of 20 t were used to manufacture all laminates. After curing for five days, the laminates were brushed and cut to the desired dimensions.

The materials for the laminates were selected through a randomized process, followed by a visual inspection for any defects. The laminates had dimensions of 98 cm × 18.5 cm × 5 cm (Figure 2). Three bending samples were obtained from each block. The sample size was estimated based on preliminary studies, considering a 5% error. This led to the production of 24 samples for each material (i.e., wood laminate, bamboo laminate, and 4 types of confined bamboo laminate), totaling 144 test specimens for analysis [21]. The composite laminates were constructed using different ratios of softwood and bamboo, approximately 20, 40, 60, and 80% of confined bamboo.

For the bending test, equipment with a load capacity of 300 kN, a variable resolution of 0.01 N, and a test speed of 6 mm/min was used. The cross section of the samples had a width (w) and height (h) of 5 cm, and a free span of 90 cm, resulting in an L/h ratio of approximately 18. The test loads were applied at 30 cm from each support [33,34]. The elastic modulus of tension, compression, and shear were measured using strain gauges. Additionally, a deflectometer (Model Epsilon 3540-012M-ST) was installed at the middle of the span (Figure 3).

The laboratory collected a substantial amount of data, including specimen dimensions and measurement instrument records. To adequately represent the statistical summary of the processed data, box and whisker plots were constructed, following the convention shown in Figure 4d.
3 Results and discussion

3.1 Control of variables and outliers

The test results were adjusted to account for variations in moisture content in order to obtain representative results of conditions where the moisture content is 12% [35,36]. Additionally, the thickness and density of the materials were controlled to ensure that the samples were representative of each group (Figure 4). The material thickness and density were controlled by ensuring that the coefficient of variation (CV) does not exceed 5%.

3.2 Modulus of elasticity (MOE) results

The study analyzed the MOE measurements and identified outliers by applying a factor of 1.5 times the interquartile range.
range, as depicted in Figure 5. To ensure the data’s normal distribution, the researchers employed the Shapiro–Wilk normality test. Furthermore, Levene’s test was performed to determine homoscedasticity; the results showed that the variances were not homogeneous, as presented in Table 2.

A statistical test was conducted to compare the mean values of data groups and validate the increase in resistance of the confined bamboo laminate. The non-parametric Kruskal–Wallis test with a significance level of $\alpha = 0.05$ was used. The null hypothesis, which stated that the mean values were equivalent to one another, was rejected ($p = 7.96 \times 10^{-9} < \alpha = 0.05$). This result indicates that the averages are statistically different.

To visually illustrate the variations in average MOE values, the bending strength ($f_b$) was plotted against unit

**Table 2: Shapiro–Wilk normality test ($\alpha = 0.05$) for MOE and Levene’s test**

<table>
<thead>
<tr>
<th></th>
<th>Wood</th>
<th>20% bamboo</th>
<th>40% bamboo</th>
<th>60% bamboo</th>
<th>80% bamboo</th>
<th>Bamboo</th>
</tr>
</thead>
<tbody>
<tr>
<td>$n$</td>
<td>19</td>
<td>18</td>
<td>19</td>
<td>24</td>
<td>21</td>
<td>19</td>
</tr>
<tr>
<td>$W$-stat</td>
<td>0.936</td>
<td>0.929</td>
<td>0.978</td>
<td>0.938</td>
<td>0.929</td>
<td>0.972</td>
</tr>
<tr>
<td>$p$-value</td>
<td>0.222</td>
<td>0.185</td>
<td>0.922</td>
<td>0.151</td>
<td>0.133</td>
<td>0.818</td>
</tr>
<tr>
<td>Normal</td>
<td>ok</td>
<td>ok</td>
<td>ok</td>
<td>ok</td>
<td>ok</td>
<td>ok</td>
</tr>
<tr>
<td>Levene’s test</td>
<td>$6.86 \times 10^{-6} &lt; 0.05 = \alpha$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

$n = 24$ samples for each material – outliers. Source: Author.

**Figure 5:** Box and whisker diagram for MOE. Source: Author.

**Figure 6:** General graph of bending stress ($f_b$) vs unit strain ($\varepsilon$) to represent both flexural stiffness and ultimate stress. Source: Author.
strain ($\varepsilon$) in Figure 6. The graph compares the primary materials, wood (represented by the color red), and bamboo (represented by the color black). The behavior of composite materials depends on the constituent percentages, as dictated by the mixing rule. Nevertheless, when bamboo is confined by 60 and 80%, the bending stiffness of the specimens significantly exceeds that of specimens made solely of bamboo with the same dimensions and configuration. The bamboo specimen confined to 40% exhibits behavior similar to that of the bamboo-only specimen, while the specimen with 20% confined bamboo approximates its behavior. Additionally, the confined bamboo laminates with softwood demonstrate a substantial improvement compared to an equivalent wood specimen.

The mathematical model to determine the MOE with the thickness of the core of the confined bamboo laminate obtained in this study based on the experimental measurements, is presented in Figure 7. The figure also compares the actual MOE values of this type of laminate to their theoretical values obtained using the mixing rule [2]. The results indicate that the optimal bamboo-softwood ratio is 46% bamboo and 54% softwood, resulting in an MOE that is 16.6% higher than the value predicted by the mixing rule.

### 3.3 Modulus of rupture (MOR) and maximum shear results

To identify any unusual data points in the MOR and maximum shear measurements, the interquartile range was multiplied by a factor of 1.5. This analysis showed that there were no outliers present in the data (Figure 8). Subsequently, to ensure that the data followed a normal distribution, a Shapiro–Wilk test was carried out, Levene's test was used to determine homoscedasticity, and ANOVA test was used to compare the averages of different data groups, and the results are tabulated in Table 3.

The mathematical model to determine the MOR and maximum shear ($\tau_{\text{max}}$) is presented in Figure 9. The figure depicts the relationship between the thickness of the confined bamboo laminate and the MOR and maximum shear.

**Figure 7**: Second degree polynomial regression for MOE. Source: Author.

**Figure 8**: Box and whisker diagram for (a) MOR. (b) Maximum shear $\tau_{\text{max}}$. Source: Author.
Additionally, it compares the experimental MOR and $\tau_{\text{max}}$ values to their theoretical values. The optimal bamboo-softwood ratio was determined to be 48% bamboo and 52% softwood, resulting in a MOR that is 18.32% higher and a maximum shear ($\tau_{\text{max}}$) that is 19.10% higher than their theoretical values (as shown in Figure 9).

Figure 10 presents the load and resistance factor design (LRFD) design values for the confined bamboo laminate that was tested, including the deterministic coefficient of the design curves. These values are influenced by several factors, such as the quality of the materials, the adhesives utilized, and the pressing techniques employed. It is noteworthy that the design values were established by the standard guarantee that 95% of the tested material will be within the appropriate range, except for the MOE, which will be calculated as the average [37–39]. According to technical standards, these materials display normal behavior and may have a 5% margin of error in their design values [40].

### Table 3: Shapiro–Wilk normality test ($\alpha = 0.05$) for (a) MOR and (b) maximum shear $\tau_{\text{max}}$

<table>
<thead>
<tr>
<th></th>
<th>Wood</th>
<th>20% bamboo</th>
<th>40% bamboo</th>
<th>60% bamboo</th>
<th>80% bamboo</th>
<th>Bamboo</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a) $n$</td>
<td>19</td>
<td>18</td>
<td>19</td>
<td>24</td>
<td>21</td>
<td>19</td>
</tr>
<tr>
<td>W-stat</td>
<td>0.971</td>
<td>0.951</td>
<td>0.939</td>
<td>0.937</td>
<td>0.954</td>
<td>0.968</td>
</tr>
<tr>
<td>p-value</td>
<td>0.798</td>
<td>0.436</td>
<td>0.255</td>
<td>0.136</td>
<td>0.396</td>
<td>0.741</td>
</tr>
<tr>
<td>Normal</td>
<td>ok</td>
<td>ok</td>
<td>ok</td>
<td>ok</td>
<td>ok</td>
<td>ok</td>
</tr>
<tr>
<td>Levene’s test</td>
<td>0.596 &gt; 0.05 = $\alpha$</td>
<td>$F = 11.03$</td>
<td>$p$ value = $5.91 \times 10^{-9}$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ANOVA test</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

| (b) $n$ | 19   | 18          | 19         | 24         | 21         | 19     |
| W-stat | 0.973| 0.946       | 0.940      | 0.929      | 0.946      | 0.971  |
| p-value | 0.826| 0.372       | 0.259      | 0.091      | 0.290      | 0.790  |
| Normal | ok   | ok          | ok         | ok         | ok         | ok     |
| Levene’s test | 0.654 > 0.05 = $\alpha$ | $F = 11.89$ | $p$ value = $1.42 \times 10^{-9}$ |
| ANOVA test |      |             |            |            |            |        |

$n = 24$ samples for each material – outliers. Source: Author.

**Figure 9:** Results obtained from bending tests, second degree polynomial regression for (a) MOR. (b) Maximum shear $\tau_{\text{max}}$. Source: Author.
3.4 Bending mechanical characterization

The design values of the confined laminates under study were determined as a function of the thickness of their core. These values, except for the MOE, were obtained at the fifth percentile, since the design value of the MOE corresponds to the data average, which naturally has a high variance. Therefore, to establish the design value of the MOE for these materials with a high degree of reliability, an alternative method is needed.

To account for the natural variation in density and fiber distribution of wood and bamboo, which are both natural products, a statistical predictive mathematical model was proposed in this study. Due to the heterogeneous nature of plants, it is inevitable that the material’s properties will vary from sample to sample. Thus, a minimum of three specimens for each test is proposed to ensure statistical control.

Additionally, a t-student hypothesis test was performed between the population averages and the sample average to estimate the MOE of a confined bamboo laminate as a function of core thickness at a significance level of $\alpha = 5\%$. The inference of the design value was formulated statistically in equations (1) and (2).

\[
H_0 : \mu \leq \bar{X} \\
H_1 : \mu > \bar{X} \quad : \quad n = 3 \quad : \quad \alpha = 0.05 \quad : \quad gl = 2, \quad (1)
\]

\[
t = \frac{\bar{X} - \mu}{s/\sqrt{n}} \quad : \quad \bar{X} = \frac{t \times S}{\sqrt{n}} + \mu \quad : \quad \quad (2)
\]

In this case, the CV is equal to the average of the experimental values measured in the laboratory (Table 4).

The results demonstrate that the relationship between the MOE and the core thickness of a confined bamboo laminate can be graphically represented as shown in Figure 11. The average MOE ($\mu$) of the total population is represented by the blue curve, while the sample average MOE ($\bar{X}$) is represented by the red curve. The segmented orange line represents the theoretical MOE values. Both curves are modeled using a second-degree polynomial and meet the statistical requirements specified in equations (1) and (2).
The proposed method for characterizing confined bamboo laminates involves several steps, as summarized below: First, appropriate wood and bamboo materials are selected for the study. Next mechanical characterization of these materials is conducted, including a composite section consisting of a 50–50% ratio of wood and bamboo. It should be noted that the observed improvements in the resistance of confined bamboo laminates over sole bamboo laminates can be extrapolated to other cases, provided the manufacturing processes and materials used are similar to those used in this study. However, it is important to periodically update the calibration curves as materials of natural origin exhibit high coefficients of variation.

The MOE of the materials is parameterized, and the design values are calculated at the fifth percentile. To verify the results of the study, additional experimental tests of the materials are performed using a minimum of three specimens. Finally, the design values of the laminates

![Figure 11: Statistical inference of the MOE (X̄) based on the percentage of confined bamboo with radiata pine. Source: Author.](image1)

![Figure 12: MOE validation test (radiata pine). Source: Author.](image2)

![Figure 13: Validation test of strength in bending Fb and design values for LRFD (Radiata pine). Source: Author.](image3)
are correlated with their MOE and the thickness of their confined bamboo core.

### 3.5 Model validation

The proposed model was validated through the manufacturing of additional laminates using two types of wood: Radiata Pine and Caribbean Pine. To assess whether the mathematical model accurately predicts the design values, groups of three specimens with similar thicknesses of confined bamboo were tested using the same manufacturing processes. The results of these tests are presented in Figures 12–15, which serve to confirm the initial findings.

#### 3.5.1 Radiata pine

This section validates the hypothesis of this study by presenting the MOE experimental values of three radiata pine specimens and three specimens of confined bamboo laminate, as depicted by the purple and green dots, respectively, in Figure 12. The design values of these materials are represented by the red curve, and the design value of the confined bamboo specimens at 34% is indicated by the green square.

Figure 13 shows the experimental values of the bending resistance of three new wood specimens and three confined bamboo laminate specimens used to validate the hypothesis of this study, as shown by the purple and green dots, respectively. The red curve in Figure 13 represents the design values of the LRFD method for measuring bending resistance at the fifth percentile.

#### 3.5.2 Caribbean pine

Additionally, the proposed hypothesis was also validated with Caribbean pine. To achieve this objective, an additional twelve tests were conducted in groups of three specimens for wood laminate and confined bamboo laminate

![Figure 14: MOE validation test (Caribbean pine). Source: Author.](image)

![Figure 15: Validation test of bending resistance (Fb) and design values calculated through the LRFD method (Caribbean pine). Source: Author.](image)
with cores of varying thicknesses (33, 34, and 54%). The results of these tests are shown in Figures 14 and 15. The colored dots in the figures represent the experimental data, while the red curve indicates the design values for the materials in terms of MOE and bending resistance ($F_b$), respectively.

3.6 Uses and limitations

The objective of the described composite material is to provide a viable alternative to laminated and sawn wooden beams in construction. However, a limitation arises when the spans exceed 2.70 m because the overlapping of bamboo strips can compromise their rigidity and strength. Other researchers have noticed that in beams, large dimensions introduce additional variables that affect the bending performance of composite laminates made of wood and bamboo [24]. Therefore, further investigation is needed to address this topic.

The numerical model developed to predict the mechanical properties of the design has certain limitations, and its accuracy depends on the materials used and the manufacturing process of the laminates. Therefore, if any procedure varies from one manufacturer to another, the design values will differ, and as a result, the calibration curves will be unique for each manufacturer. The mechanical properties of wood and bamboo laminates depend on the selection of raw materials, brushing, gluing, pressing, curing, and additives. Processes with stricter quality controls and standardized procedures yield better results and lower CV.

4 Conclusion

This study characterized the bending mechanical properties, including MOE and MOR, of confined laminated bamboo using softwood. The composite materials exhibited improved properties compared to those estimated using the rule of mixtures. An optimal composite ratio of 46–54% bamboo-wood resulted in a 16.6% increase in MOE and an 18.3% increase in MOR, surpassing theoretical analysis.

A statistical model was developed to obtain design values for MOE, $F_b$, and $G$ based on the thickness of confined bamboo. Validation using 18 additional beams confirmed compliance with normative standards. This model provides an effective alternative to visual and mechanical classification systems.

Confined bamboo laminates, when combined with softwoods, exhibit improved stiffness and resistance to bending and parallel shear, making them viable and environmentally sustainable options for beam construction. However, the commercial limitation regarding the length of bamboo strips requires further research to explore techniques for overlapping strips and evaluate their performance on longer span beams.

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Conflict of interest: Authors state no conflict of interest.

Data availability statement: The datasets generated and analyzed in the current study are available from the corresponding author on reasonable request.

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