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DEVELOPMENT OF MORTISE AND TENON JOINT FROM LAMINATED BAMBUSA VULGARIS FOR FURNITURE PRODUCTION

Oluwatoyin Q. HASSAN-AJAO*
Dr.Engr. - Department of Wood Products Engineering, Faculty of Technology, University of Ibadan
PMB 200005 UI Ibadan
E-mail: qudirat.toyinajao@gmail.com Tel: +2347032933802

Nureni N. ADEWOLE
Prof.Engr. - Department of Wood Products Engineering, Faculty of Technology, University of Ibadan
PMB 200005 UI Ibadan
E-mail: nureniadedapoadewole@gmail.comTel: +23433963707

Musiliu A. ONILUDE
Prof - Department of Wood Products Engineering, Faculty of Technology, University of Ibadan
PMB 200005 UI Ibadan
E-mail: profonilude@gmail.com Tel: +2348052174815

Abstract:

The increasing interest in sustainable materials for furniture production has positioned bamboo as a promising alternative to conventional timber due to its rapid renewability, readily available, high strength-to-weight ratio, and high mechanical properties. But there is dearth of information on the design parameter of Mortise and Tenon Joints (MTJ) produced from Bambusa vulgaris (Bv). Therefore, this study evaluates the design performance of MTJ constructed from Bv for furniture applications. Five MTJ specimens were fabricated from treated bamboo culms and were secured with nails, metal bracket and adhesive were experimentally and theoretically evaluated. Design parameters such as tenon depth and length. A tolerance limit value of 0.1mm was chosen to secure higher joint reliability in the furniture frame. A 3 - point mechanical testing was conducted using a Universal Testing Machine (UTM) under controlled bending conditions to determine load deflection response, peak load and ultimate bending strength, and joint stiffness were determined. These MJT parameters were used for the structural design of the Bamboo Chair Frame (BCF). The BCF was designed and 5 model samples constructed for evaluation, on the UTM. The design MTJ parameter was 6 and 15mm while the predicted were 5.6 and 14.98 for the depth/width and length with allowance of 0.1mm, respectively. The expected load on the BCF was four times greater than the load applied. Laminated Bambusa vulgaris was successfully utilised for the construction of structural furniture with high structural integrity.

Key words: *Laminated Bamboo joints; Mortise and tenon joint; Bamboo chair frame, Furniture design.*

INTRODUCTION

The increasing demand for sustainable and environmentally friendly materials in furniture manufacturing has intensified interest in bamboo as an alternative to conventional timber (Seman et al. 2025). Bamboo is widely recognized for its rapid growth rate, renewability, high strength-to-weight ratio, and favorable mechanical properties, making it suitable for structural and semi-structural applications (Hassan-Ajao at al 2024). Despite these advantages, the performance of bamboo in furniture construction is highly dependent on the effectiveness of its jointing systems, which remain a critical factor in ensuring structural integrity and durability (Madhushan at al. 2023, Sewar et al. 2024).

Joinery plays a fundamental role in furniture design, as it governs load transfer, stability, and resistance to failure under service conditions (Sydor and Stańczyk 2025). Xu et al. (2025) noted that mortise and tenon joint is one of the most widely used joint due to its ease of construction, simplicity, efficiency, and strong mechanical interlocking characteristics in woodwork. Chen et al. (2025) stated that when mortise and tenon joint adapted for bamboo, however, its performance can differ significantly from that in solid wood. due to bamboo morphology. These inherent material characteristics introduce challenges such as localized crushing, splitting, and reduced bonding surface area, which may affect joint strength and stiffness (Luo et al. 2025, Mohinderu et al. 2026).

Luepongsak et al. (2002) documented the types of loading on joints, these are often subjected to cyclic loads arising from daily use, including seating, and leaning. Under such conditions, the mortise and tenon joint must resist combined stresses such as shear, tension, and compression. Therefore, evaluating the behavior of laminated bamboo-based mortise and tenon joints under cyclic loads is essential for determining their

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[*] Corresponding author

suitability in furniture design and development. The understanding of laminated bamboo-based mortise and tenon joints load-bearing capacity and failure mechanisms provides valuable insight into optimizing joint geometry for ease of construction. Although several studies have explored bamboo as a construction material, limited attention has been given to the detailed mechanical evaluation of its traditional joinery systems under realistic loading conditions Sewar et al. 2024.

Smardzewski, (2015) explained that a chair frame is subjected to dozens and hundreds of unpredictable loads and abuse, while such piece of furniture has ultimate strength capacity after construction. Furniture structure is then exposed to normal or abusive loads, and its strength would be expected to reduce because of fatigue (Smardzewski 2015). Joints are the weakest part of furniture structure, so very typical failures may occur due to lose or failed joints rather than fractures in legs or other members (Hassan-Ajao 2023). Tankut and Tankut stated that when furniture joints are overstressed and exceed their elastic limit, the structure fails. It is important that furniture joints must be designed to resist all loads imposed in service. Evaluating the behavior of laminated bamboo-based mortise and tenon joints under cyclic loads is essential for determining their suitability in furniture design. Therefore, this study aimed to investigate the reliability of laminated bamboo chair frames constructed with mortise and tenon joints.

Objectives

The objectives of the study are to:

i. bamboo culm collection, preparation and processing into boards;
ii. design and fabrication of Mortise and tenon joint;
iii. analyze the rigidity of bamboo-based joint (experimentally & theoretical);
iv. design and evaluate a chair frame using baseline data obtained through experimentation;
v. fabricate a chair frame using bamboo-based intermediate raw material.

METHOD

Bamboo Collection and Preparation

The Bamboo (*Bambusa vulgaris*) culms samples utilised for the study were harvested from the bamboo cluster located beside the admission office, Faculty of Technology Area, University of Ibadan (Fif. 1.a), where matured bamboo culms were carefully selected from identified bamboo culm stock location. The culms were further processed using bamboo conversion machine available in Wood Products Engineering Departmental Workshop, to attain strips of uniform dimensions as presented in Plate 1e. The strips were treated using boric acid-borax chemical preservative solution at a ratio of 1:5 (boric acid:borax), through deep soaking treatment process as shown on Fig. 2.

Fig. 1.
Conversion process of bamboo culms to uniform dimensioned strips
a - Location where bamboo culms were obtained, b - Bamboo culms for conversion process, c - Cross-cut bamboo culms, d - Stacked bamboo culms, e - Uniform dimensioned bamboo strips.

Fig. 2.
Soaked bamboo strips during preservation process.

The uniform bamboo strips were further processed into an intermediate material by laminating using Poly Vinyl Acetate (PVA) adhesive with the trade name “Top Bond” to produce laminated bamboo lumber as presented in Fig. 3.


a. b. c. d. e. f.

Fig. 3.
Process of phenol-formaldehyde adhesive application.

Design and theoretical analysis of Mortise and tenon joints

The Mortise and tenon square configuration of 150 by 150 joint geometry was devised as shown in Fig. 4. The structural behavior of the joint was evaluated theoretically using anatytical procedures proposed by Tankut et al. (2003). The internal bending force acting on each tenon joint was structurally determined using as presented in Equation 1. The corresponding bending stress generated in a round shape of a tenon was used in Equation 2, as suggested by Tankut et al. (2003).

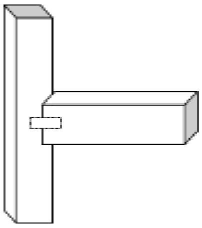


Fig. 4.
Sketch of coupled mortise and tenon joint.

$$F_4 = \frac{f_2 \times h}{n} \qquad \ldots \qquad \text{Equ 1 (Tankut et al. 2003)}$$

$$S_4 = \frac{32 f_4}{\pi \ D^3} \qquad \ldots \qquad \text{Equ 2 (Tankut et al. 2003)}$$

where:

f_2 = force applied to the side frame in a front back direction (N) = 2 KN;
h = vertical distance to the load point (M) = 250mm;
n = number of tenon = 10;
D = diameter of the tenon = 6 mm;
f_4 = bending force acting on the end of the stretcher equals 47.706 Nm and the
S_4 = corresponding bending stress = 2.24967 N.

If the frame leg must be supported by side stretchers, the necessary correction factor to render the ordinary methods of analysis as applicable. The semi-rigid joint parameter for the joints was computed using Equation 3 according to Tankut et al. (2003).

$$\Phi = \frac{ML}{EI} \qquad \ldots\ldots \qquad \text{Equ 3 (Tankut et al. 2003)}$$

where:

M = the couple (Nm) = 5963.25375;
E = Modulus of Elasticity = 6100;
L = a constant = 0.1;
I = moment of inertial for a tenon (m^4) = 23,333.33;
No correction factor necessary, the Z-values, Φ is minimal and equals to 4.2×10^{-6}.

Construction of T-Shaped Mortise and Tenon Joints

The mortise and tenon produced from the laminated bamboo lumber. The bamboo lumber was cut into a square configuration of 4 by 4mm with a length of 150mm, and the mortise was grooved at the middle at a depth of 1.8mm while the tenon was cut to have ¾ remaining at the middle. A gap of 0.1mm was maintained between the tenon and the mortise to facilitate assembly as shown in Fig. 5.

a. ***b.***

Fig. 5.
Mortise and Tenon Joint Parts
a - Mortise groove; b – Tenon.

The joints samples as presented in Fig. 6.a were secured using 3 different methods, adhesive, nails, and metal bracket were used separately. Commercial PVA adhesive ("Top Bond") was used for the adhesive-bonded joint samples, three 18.75mm (3/4") nails were used for the nail joint samples, and four 12.5mm (1/2") screws were used to secure the two metal brackets used for the metal bracket joint samples. Five joint samples as presented in Fig. 6.b were produced for each of the groups resulting in a total of fifteen joint samples for their structural integrity through experimentation.

Experimental Evaluation of Joint Performance

The structural performance of the fabricated joints was evaluated according to ISO 7174-1:1988 and ISO 7173:1989 using the Universal Testing Machine (UTM) with a load capacity of 4000N, available in the Wood Products Engineering Departmental laboratory as presented in Fig. 6.c. Each specimen was mounted using a specially fabricated testing jig and loaded until deformation occurred. The performance parameters recorded are presented in Table 1.

a. ***b.*** ***c.***

Fig. 6.
Laminated bamboo joints samples
a and b - Laminated bamboo joints samples; c - Joints samples held with fabricated jig during experimentation.

Table 1

Deflection on Joint Samples

Peak force (N/mm^2)	Force (N/mm^2)	Allowable force (Pf-F)(N/mm^2)	Deflection (mm)
	Adhesive		
9	8.02	0.98	37.06
8.91	8.36	0.55	34.28
9	8.46	0.54	25.99
8.94	8.33	0.61	24.05
8.92	8.01	0.91	32.89
Mean 8.954	8.236	0.718	30.854
	Nails		
9.01	7.9	1.11	27.52
8.97	8.24	0.73	19.97

9.02	8.04	0.98	19.53
9.03	7.98	1.05	41.18
9	8.17	0.83	45.4
Mean 9.006	8.066	0.94	30.72
Metal bracket			
9.15	8.19	0.96	18.54
9.2	8.05	1.15	19.84
9.15	8.24	0.91	22.15
9.02	8.15	0.87	20.06
9.08	8.07	1.01	21.23
Mean 45.6	40.7	0.98	20.364

Joint Optimisation

Joint dimensions obtained from the theoretical structural analysis were further optimized using Response Surface Methodology (RSM) implemented in Design-Expert software. Among the available experimental designs, the Box–Behnken design was selected because of its efficiency in modelling nonlinear interactions while requiring fewer experimental runs. The optimized design variables were evaluated statistically to determine the most suitable joint dimensions capable of maximizing structural performance while minimizing deformation.

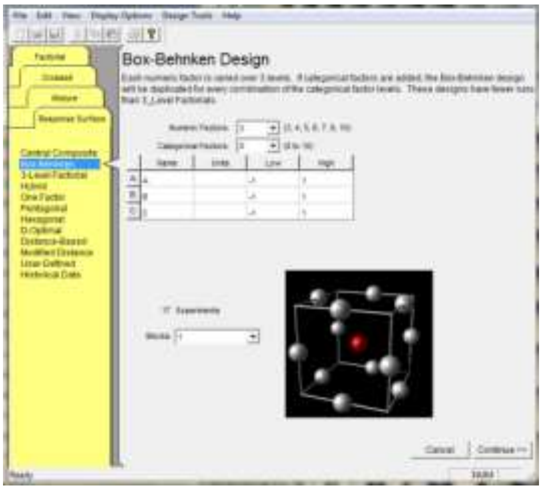


Fig. 7.
The presentation of Box-Behnken design of Respond Surface Methodology.

Bamboo Chair Frame Strutural Design

The office chair frame was design to support adult weight of 120 kg body weight.
Expected load are Live load = 120kg x 9.81 = 1177.2N and self-load = 800g x 9.81=7.848 N.
Factor of safety used was adopted form Larsen and Enjily (2009) = (*1.4 x dead load + 1.6 x live load).*
Thus, the critical load utilized for the design is approximately 2 KN.

Frame Seat/Slat

The seat slats were designed as simply supported members subjected to uniformly distributed loading. Bending moment, fibre stress, deflection, and shear stress analyses.

Then the induced bending moment on the slat can be determined using the Equation 4 used by Khurmi and Gupta (2005).

$$\text{Bending Moment} = \frac{wL^2}{8}\ \text{(Nm)} \quad \ldots\ldots \qquad \text{Equ 4 (Khurmi and Gupta 2005)}$$

where: W = load (N) = 1894.5N ≈ 2KN;
L = length of seat (mm) = 500mm = 0.5m.

Induced bending moments 62500 Nm on the seat frame of area 550 by 500 mm

The seat loading arrangement was flat-wise as shown in Fig. 8a. and the orientation of each of the slats in the seat arrangement is shown in Fig. 8b. Since the slat members are to directly receive the load imposed by the chair user, the slat member dimensions were determined using Equations 4, 5, and 6 recommended by Khurmi and Gupta (2005).

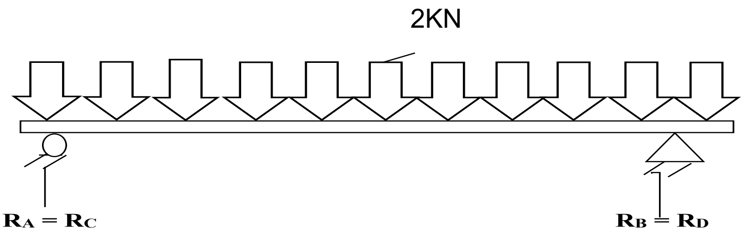
$$m = S\ x\ fb \qquad \ldots \qquad \text{Equ 4}$$

$$d\ = \sqrt{\frac{6m}{b\ x\ fb}} \qquad \ldots \qquad \text{Equ 5}$$

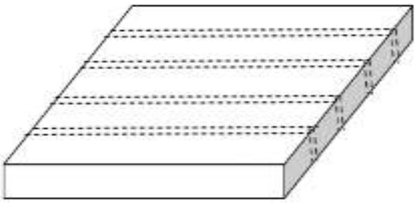
$$\text{section modulus} = \frac{db^2}{6} \qquad \ldots \qquad \text{Equ 6}$$

where:

m = induced moment = 0.06 x 10^6 Nm;
s = section modulus = $\frac{db^2}{6}$ = 15,312.5 mm^3;
fb allowable fiber stress;
b = chair frame;
width = 500mm;
fb = allowable fiber stress = 0.570 N/mm^2;
d = 35.4 mm.



a.



b.

Fig. 8.
a - Assume loading system for each of the seat slat member; b - Seat slats arrangement.

The $M_{induced}$ was shared equally among the 5 slats, then, each slat had induced fiber stress of 0.026 N/mm^2**.** $f_{b\ allowable}$ from the experimental results = 0.570N/mm^2.

The design is safe since f_b allowable is 0.570 N/mm^2 > f_b induced 0.026 N/mm^2.

Therefore, the seat of the frame was made with 5 slats with each dimension 500 x 75 x 35 mm (L x W x T) and with a spacing of 10 mm in between adjacent slats.

$$\text{Deflection} = \frac{5wl^4}{384EI} \qquad \ldots.. \qquad \text{Equ 7}$$

where:

W = load = 2 kN;
L = length of the seat (mm) = 550mm;
E = 6100N/mm;
I = $\frac{db^3}{12}$ = moment of inertia mm^4;
d = 35 mm, b = 75 mm.

$$I = \frac{db^3}{12} = 1{,}230{,}468.75\ \text{mm}^4 \qquad \ldots.. \qquad \text{Equ 8}$$

Deflection$_{(induced)}$ = 0.032 mm
Maximum deflection $_{(allowable)}$ obtainable is from L/180 = 3.05 mm
Design is safe, since deflection$_{(allowable)}$= 3.05 mm > deflection$_{(induced)}$ = 0.032 mm

$$\text{Shear force}_{(induced}\ (f_v) = \frac{1.5\,V}{bd} \qquad \text{........} \quad \text{Equ 9}$$

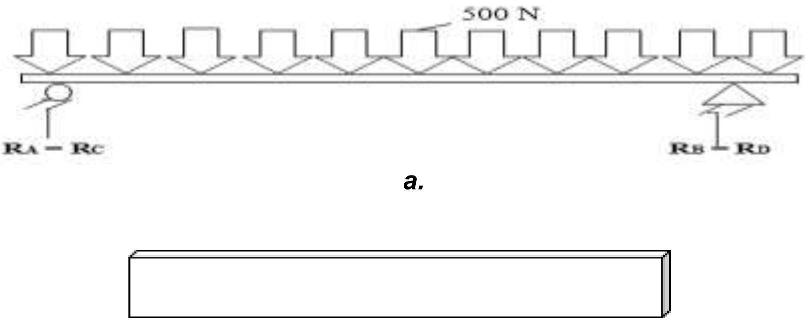
where:

b = width = 550 mm;
d = depth (500 mm) of the frame;
$V = \frac{wl}{2}$;
l= length =500;
w= w $_{(induced)}$ load.

Recall that the Seat load is shared equally among the 5 slats, thus
W$_{(induced)}$ = 400 and V = 100,000 N/mm
Shear force$_{(induced)}$ (f_v) = 0.55
From the experimental test, f_v allowable = 1.68 N/mm^2,
Therefore, the design is safe since $f_{v\ allowable}$ 1.68 N/mm^2 > $f_{v\ induced}$ 0.55 N/mm^2

Frame rail Design

The section of the frame that receives both the transmitted load and the self-weight of the seat. Rails on the frame are loaded edge-wise as shown in Fig. 9a and b.



a.

b.

Fig. 9.
a - Assume loading system for each of the rail member; a - Rail member orientation.

Load transferred from the seat + weight of the seat = 1894.5072 N;
Self-weight of the rail is assumed to be 13.734 N.
Then the total load expected on the rail is 1908.24 N ≈ 2 kN.
The load induced on the rails was equally shared by all of the members.
Then, the load on a rail member was 500 N.

The value determined for the induced bending moment on the rail was 15,000 Nm. For the sake of this design, the orientation of each rail in the chair frame arrangement presented in Fig. 9a. The rail members dimensions were determined using Equations 4, 5, and 6. suggested by Khurmi and Gupta (2005), and previously used for slate depth determination.

$$d = 45.8\ \text{mm, section modulus} = \frac{db^2}{6} \qquad = 42{,}187.5\ \text{mm}^3$$

The M$_{induced}$ was shared among the 4 rails equally, then, each rail member had an induced fiber stress of 0.012 N/mm^2**.**, allowable value for fb is equal to 0.570N/mm^2 from the experimental results.

Therefore, the design is safe since the $f_{b\ allowable}$ is 0.570 N/mm^2 > fb-$_{induced}$ 0.012 N/mm^2.

The frame side rails dimension is given as 500 x 75 x 45mm (L x W x T) while, the dimension of the front and back rail members is 550 x 75 x 45mm (L x W x T).

$$\text{Deflection}_{\ (induced)} \ = \ \frac{5wl^4}{384EI}$$

where:

W = load = 2 kN;
L = length of the seat (mm) = 550mm;
E = 6100N/mm.

$$I = \frac{db^3}{12} = \text{moment of inertia mm}^4,$$

where:

d = 45
b = 75
note, the chair frame requires 4 members of 45 x 75mm rail members

$$I = \frac{db^3}{12} = \frac{45\ x\ 75^3}{12} = 1{,}582{,}031.25\ \text{mm}^4$$

Deflection $_{\text{(induced)}}$ $= \frac{5\ x\ 2\ x\ 10^3\ x\ 550^4}{384\ x\ 6100\ x\ 1230468.75} = 0.54$ mm
Maximum deflection $_{\text{(allowable)}}$ was obtained from L/180 = 3.05 mm
Design is safe, since deflection $_{\text{(allowable)}}$ is 3.05 mm > deflection $_{\text{(induced)}}$ is 0.54 mm

Shear index of rail members was determine using the Equation 9 suggested by Khurmi and Gupta, (2005), as preciously used for the seat Shear index.

$$\text{Shear force}_{\text{(induced}}\ (f_v) = \frac{1.5\ V}{bd}$$

where:

b = width = 75 mm;
d = depth (45 mm) of the frame;
$V = \frac{wl}{2}$;
l= length =500;
w= w $_{(induced)}$ load.

The induced load is shared equally among the 4 rail members:
$W_{\text{(induced)}}$ = 500.
V = 125,000N/mm.
Shear force $_{\text{(induced)}}$ (f_v) = 55.5N/mm^2.
Shear force from the experimental test, f_v allowable = 1.68N/mm^2.
The design is **NOT** safe since $f_{v\ \text{allowable}}$ is 1.68 N/mm^2 less than $f_{v\ \text{induced}}$ 55.5N/mm^2 using the dimension of the members 500 x 75 x 45 mm (L x W x T).

Lateral stability check was done on the designed dimension for the lateral stability requirement. Lateral stability is the ratio of depth to breadth that generates a value of 0.6, implies lateral support needed. Therefore, two lateral 75 x 45mm (W x T) members were required and to be fix at a distance of 100mm from the ground level.

Frame legs

The chair frame legs are considered and designed as (compression members) columns. These components are subjected to load transfer from the seat and rail, as well as their own weight. The load induced on the leg members is the summation of the loads induced by the self-weight of the seat, the self-weight of the rail and the induced load from the user equals 1908.2412N.

where:

Cp = column stability factors;
C = 0.9 glue laminated timber;
F_c, gotten from the experimental result 0.00214N/mm^2;
F_{ce} is thus K_{ce} *= 0.3 for visually graded lumber;*
E = modulus of elasticity = 6100N/mm (gotten from experimental analysis);
slenderness ratio = $\frac{L_e}{r_g}$;
L_e= effective Length (both ends pinned);
r_g = radius of gyration = $\sqrt{\frac{I}{A}}$;

I = moment of inertia= $\frac{bd^3}{12}$;
b = 750;
d = 45;
A= area = l x b;
l = 700.

Therefore, L = 700mm, r_g = 3.29 mm, slenderness ratio = 212.53, I = 569531.25 mm^4, A = 52,500 mm^2, F_{ce}= 7.56 N/mm^2 and their ratio = 15.6.

The allowable stress = 0.00214 N/mm^2 > calculated stress = - 0.002 N/mm^2, then, design is safe.

Construction of Chair Frame

The structural designed chair frame was scaled down by ratio 3 and Table 2 presents the cutting list of the scaled-down chair frame.

The chair frame was made from laminated Bambusa vulgaris board. The manufacturing processes involved marking out and cutting and labelling of the laminated bamboo board into required sizes using the measuring tape, tri-square, steel rule, and pencil, while cross-cut machine and a circular machine were used for the cutting. Other operation done were mortising, tenoning, assembling, and sanding, as presented in Fig. 10. Five bamboo chair frames samples were produced as presented in Fig. 11, from *Bambusa vulgaris* laminates and were constructed using adhesive bonded joint as shown in Fig. 11a.

Table 2

Cutting list for the reduced parameter of the chair frame

s/n	Member	Specification (mm)	Qty
1	Seat slat	166.7 x 25 x 11.7	5
2	Front rail	183.3 x 25 x 15	1
3	Back rail	183.3 x 25 x 15	1
4	Side rail	166.7 x 25 x 15	2
5	Stretcher	183.3 x 25x 15	2
6	Back rest (post)	200 x 25x 15	3
7	Back rest (slat)	166.7 x 25 x 11.7	4
8	Leg	233.3 x 25 x 15	4
9	Arm	200 x 25 x 15	2
	Total number of items		24

Fig. 10.
Upholstered frame construction process
a - Marking out, b - Cutting c - Labelling process d - Grinding of construction parts
e - Mortise groove, f - Tenon cut, g - Assembled components h - Clamped frame.

The fabricated bamboo chair frames were loaded vertically on the seat as the load applied was evenly distributed to all the legs. The evaluation of the laminated bamboo chair frame strength was done according ASTM D1037 on the Universal Testing Machine (UTM) as presented in Fig. 11b.

Fig. 11.
Prefabricated model bamboo chair frame and bamboo chair frame under loading.

RESULTS AND DISCUSSION

Theoretical Structural Analysis of Mortise-and-Tenon Joints

Theoretical evaluation of joints revealed that the bamboo laminated material can be used to produce robust, solid furniture. The bending force acting on the end of the stretcher, f_4, determined for the frame, is 47.706Nm, while the corresponding bending stress, S_4, is determined to be 2.24967N. The determined mortise diameter equals the tenon length that was determined to be 15mm. The bending force acting on each tenon joint was determined and used to generate semi-rigid parameter Φ, for the joints, yielding a value far less than 1, equal to 4.1×10^{-6}, indicating that no correction factor was required. The joint samples exhibited a variety of deflections with different fasteners used to keep the joints together, with slight deflection occurring on the joints at different measures as presented in Table 1. The maximum permitted force that could distort the samples, and the force (kN), which was the minimum allowable force that could deform the samples. The speed at which the samples were loaded was revealed to be -0.02kN/s, and the deflection in mm on each sample was indicated.

Experimental Performance of Bamboo Chair Joints

Fig. 12. present the failure pattern of the joint samples, none of the joints were found to be distorted in the glue line. The joints secure with bracket had the best result next by the joint samples secured with nails while, the joints secured with adhesive has the least value as presented in Fig. 13, 14 and Table 3, 4. Though the value obtained from the adhesive secure joints values was four times greater than the expected loads.

The joints strengthened with angle metal brackets yield 194N/sec mm, whereas the joints reinforced with nails give 190N/sec mm, and the adhesive-bonded joints have a breaking strength of 108N/sec mm, respectively. The junction strengthened with angle metal brackets and nails has very nearly the breaking strength or bending moment capacity strength of all the joint samples. According to the results of the variance analysis conducted in Table 3, the results of the variance analysis conducted in Table 4. The strength properties of bamboo (**Bambusa vulgaris**) joint samples shows that F_{comp} 0.000874<F_{crit} 3.885294, the method of securing the joints on the strength properties of bamboo (**Bambusa vulgaris Schrad**) samples used for the experiment, were insignificant with a 5% level of error.

a. *b.* *c.*

Fig. 12.
Replicates of joints samples after experimentation.

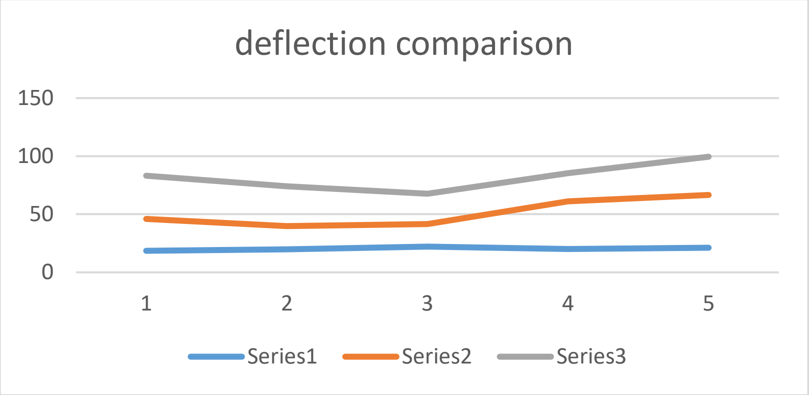


Fig. 13.
Graph of deflection againts time.

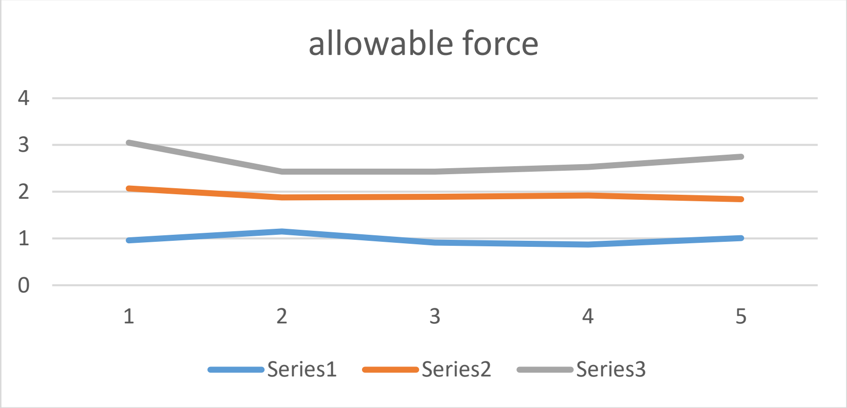


Fig. 14.
Graph of allowable force againts time.

Table 3

Average strength properties for Bambusa vulgaris Joint Samples

Strength properties of bamboo culm (N/mm^2)	Chemical preservation	Natural preservation	Control
Compression parallel to grain, F_p	24.6	24.6	25.4
Shear parallel to grain, F_v	2.6	2.6	4.0
Modulus of elasticity, E	5940	5940	5900
Modulus of rupture MOR	75.0	75.0	68.0

Table 4

ANOVA Result for the Strength Properties of Bambusa vulgaris Joint Samples

Source of variation	*SS*	*Df*	*MS*	*F*	*P-value*	*F crit*
Between groups	11894.29	2	5947.145	0.000874	0.999126	3.885294
Within groups	81644836	12	6803736			
Total	81656730	14				

Significant level $\alpha_{0.05}$

Optimization of Joint Parameters Using Response Surface Methodology

The optimal joint dimensions for an upholstered frame made from bamboo laminates evaluated by Box Benhen Experimental Design shows that the parameters used as variables influence the joint rigidity. The numerical parameters of the tenon dimensions and the categorical parameter of mortise dimensions influenced the joint rigidity. The statistical details from the theoretical Box-Benhken experimental model suggested the quadratic equation with the R^2 0.3985 for the joint while the cubic equation was aliased with the highest R^2 value of 0.8197, as presented in Table 5 and Table 6 shows the perdicted optimal parameter by the Box Benhken statistical tool. The predicted values are 14.94 and 5.86 for the optimal tenon length and diameter, respectively, as shown in Fig. 15a and b and their significant at $\alpha_{0.05}$ was presented in Table 7 and 8. As there was no significant difference in the tenon diameter as F_{comp} 5.87E-07 and F_{crit} 5.987378 also, the tenon length has F_{comp} 2.15E-07 and F_{crit} to be 5.987378, these shows that the difference between experimentation value and theoretical are similar.

Table 5

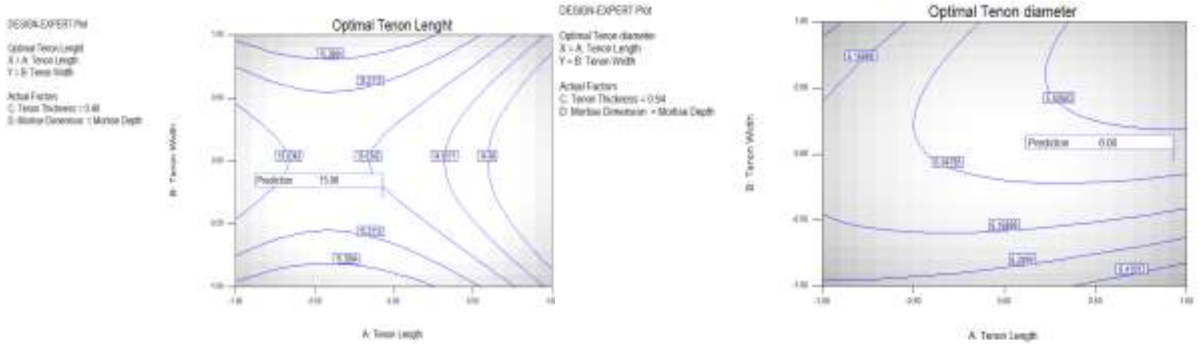
Statistical Summary details of the Box-Benhken experimental model

Source	Std. dev.	R-squared	Adujsted R-squared	Predicted R-squared	Press	
Linear	0.62	0.0376	-0.0951	-0.4335	16.40	
2FI	0.68	0.0758	-0.3260	-1.8228	32.30	
Quadratic	0.59	0.3985	0.0075	-1.7067	30.97	Suggested
Cubic	0.43	0.8197	0.4592	-10.5373	132.00	Aliased

Table 6

Optimal parameter perdicted by the Box Benhken Statistical tool

Responses	**Prediction**	Se mean	95% CI low	95% CI high
Optimal Tenon Lenght	**14.94**	0.21	14.50	15.38
Optimal Tenon Diameter	**5.86**	0.12	5.61	6.11



a. **b.**

Fig. 15.
Predicated optimal tenon length and diameter value from a curved line graph.

Table 7

ANOVA of determined tenon diameter and Optimised tenon diameter

Source of variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between groups	0.03125	1	0.03125	5.87E-07	0.999414	5.987378
Within groups	319584.7	6	53264.11			
Total	319584.7	7				

Table 8

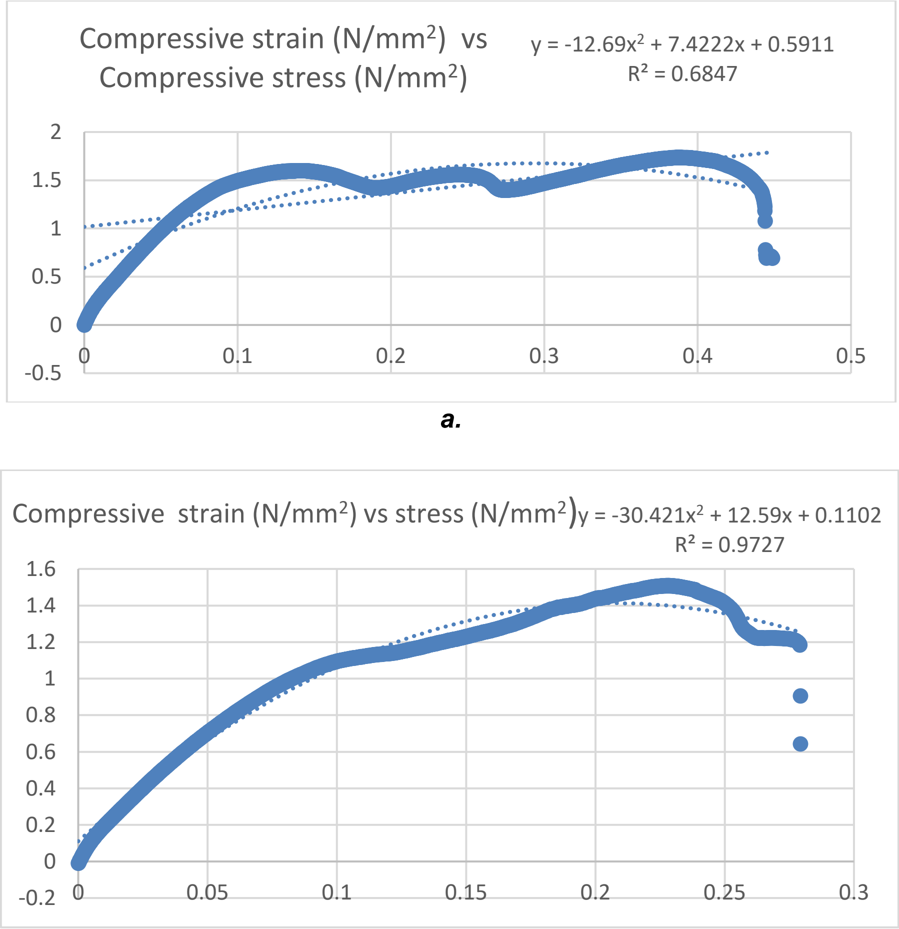
ANOVA of determined tenon length and Optimised tenon length

Source of variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between groups	0.01125	1	0.01125	2.15E-07	0.999645	5.987378
Within groups	314051.3	6	52341.89			
Total	314051.3	7				

Evaluation of laminated Bamboo Chair Frames

Fig. 16. present the failure pattern of the bamboo chair frame samples most of the failures occur in these joints as presented in Fig. 16, the strength of the joints was investigated, as the depicted in the graphical illustration shown in Fig. 17a and b.

Fig. 16.
Mode of failure observed in model frame after experimentation.



a.

b.

Fig. 17.
a - Graphical illustration of compressive strain vs compressive stress; b - Graphical illustration of compressive strain vs stress.

The maximum compressive stress that leads to failure due to tension in all the frames was significant as presented in Table 10. This indicate high elasticity nature of the laminated *Bambusa vulgaris*, the material of construction ascertain the rigidity strength of the frames as it exceeds the designed expected load. An office chair frame produced from bamboo laminated is as shown in Fig. 18.

Table 9

Strength determination of the model frame samples

Samples	Compressive stress at break (standard) (MPa)	Compressive load at break (standard) (N)	Compressive strain at break (standard)(%)
1	0.96995	3006.85149	28.20292
2	0.67050	2078.54770	41.62944
3	0.69413	2151.79771	44.87000
4	0.90549	2807.00549	27.92764
5	1.09215	3385.67160	42.11083
Mean	0.65	2685.98	36.95

Table 10

ANOVA result of the strength determination of the model frame samples

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between groups	23714085	2	11857042	112.766	1.66E-08	3.885294
Within groups	1261768	12	105147.3			
Total	24975853	14				

Fig. 18.
Produced bamboo chair frame.

CONCLUSIONS

The design and mechanical performance of laminated bamboo mortise and tenon joints for furniture applications under bending loads was successfully evaluated. joint performance is strongly influenced by geometric parameters such as tenon thickness, embedment depth, and fit accuracy. Proper alignment and precision in fabrication significantly enhanced joint strength and reduced premature failure.

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