



SHEAR PERFORMANCE OF NAIL-FASTENED SHEATHING-TO-FRAMING CONNECTIONS IN CEMENT-BAMBOO FRAME SYSTEMS

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*Corresponding Author, Received: 11 March 2026, Revised: 25 July 2026, Accepted: 28 July 2026

ABSTRACT: The increasing demand for sustainable and affordable housing has encouraged the development of engineered bamboo construction systems such as Cement-Bamboo Frame Technology (CBFT), which integrates bamboo framing with cement-based cladding. Although previous studies have demonstrated the structural performance of CBFT and bamboo shear wall systems, limited research has investigated the localized behavior of nail-fastened sheathing-to-framing connections. This study experimentally evaluated the monotonic shear behavior of CBFT nail-fastened connections at the subassembly level. Eight connection configurations with rib lath and flattened bamboo cladding were tested with five replicates each by varying cladding type, stud orientation, nail quantity, and mortar infill. Load–displacement responses were analyzed to determine yield load, ultimate load, initial stiffness, ductility, and energy absorption, while failure modes and statistical significance were evaluated. Results showed that mortar infill and increased nail quantity significantly improved connection performance. The rib lath configuration with three staggered nails and mortar infill achieved the highest initial stiffness (839.87 N/mm), yield load (1418.38 N), and ultimate load (1726.64 N), whereas the flattened bamboo configuration with three nails and mortar infill achieved the highest energy absorption (50,272.26 N·mm). Mortar confinement shifted failure from nail pull-out to nail bending and cladding damage, indicating improved load transfer. These findings provide experimental data for improving CBFT connection design. However, the results are limited to monotonic connection-level behavior and do not represent the structural response of full-scale CBFT shear wall systems.

Keywords: *Cement-Bamboo Frame Technology (CBFT), Sheathing-to-Framing Connections, Bamboo Connections, Nail-Fastened Connections, Monotonic Shear Testing*

1. INTRODUCTION

Sustainable and affordable construction is increasingly important in countries with high housing demand and exposure to natural hazards. Bamboo, often called “green gold,” is a renewable material with structural potential due to its favorable mechanical properties, rapid renewability, and low environmental impact compared with conventional materials [1,2]. Among engineered bamboo systems, Cement-Bamboo Frame Technology (CBFT) integrates bamboo framing, reinforcing mesh, and cement mortar to form structural wall panels [3,4]. Within this system, Cement-Bamboo Shear Walls (CBSWs) serve as the primary lateral load-resisting elements, transferring wind and seismic forces to the frame. In the Philippines, CBFT panels demonstrate considerable lateral load capacity while maintaining structural integrity, supporting their use in low-cost, hazard-resilient housing [4]. Mechanical characterization of local bamboo species,

particularly *Bambusa blumeana*, shows variability in shear strength parallel to fiber, emphasizing the need for careful material selection and testing [5]. Furthermore, the development of bamboo–concrete composite members has demonstrated that engineered bamboo systems can substantially improve load-bearing capacity, further highlighting the structural potential of bamboo in modern construction [6]. CBSWs evolved from traditional bahareque construction by integrating bamboo framing, reinforcing mesh, and cement plaster into engineered shear wall systems. These systems have been used in more than 4,000 housing projects worldwide, including the Philippines, Costa Rica, Colombia, and Peru [3]. When properly designed, CBSWs provide affordable, hazard-resilient, low-carbon housing and are included in structural codes in Colombia, Ecuador, and Peru [3]. Although various bamboo shear wall systems have been reported in the literature, they differ in framing materials, sheathing configurations, reinforcement details, and

connection systems. CBFT represents the Philippine adaptation of this concept by standardizing bamboo framing reinforced with cement plaster for social housing projects, reducing CO₂ emissions and improving sustainability compared with conventional concrete [1]. Recent life cycle assessment studies further demonstrated that CBSW systems can reduce embodied carbon emissions while maintaining comparable construction costs, supporting their potential as sustainable housing systems [7]. Together, these systems illustrate the evolution of engineered bamboo construction, improving structural integrity, uniformity, and lateral load resistance while meeting contemporary standards for resilient housing.

Connection behavior is widely recognized as a critical factor governing the structural performance of bamboo structures [8]. The mechanical performance of CBFT wall systems is strongly influenced by sheathing-to-framing connections, which transfer in-plane shear from cladding to the bamboo frame. Experimental and theoretical studies indicate that fastener type, placement, and spacing critically influence load transfer, stiffness, and ductility [9,10,11]. Single-nail connections tend to exhibit ductile behavior with plastic hinge formation, while multiple nails in staggered arrangements can increase shear capacity but may trigger brittle failures if poorly designed [9,12]. Additional factors, including bamboo anisotropy, node distribution, and moisture content, affect connection performance, highlighting the importance of precise fastener placement and, in some cases, pre-drilling to prevent splitting and localized failures [8,13].

Predictive models, such as the European Yield Model (EYM), are commonly used to estimate the lateral load capacity of dowel-type fasteners by considering plastic hinge formation and embedment behavior [9]. Additional studies show that cladding type and bamboo-fastener interaction also influence connection strength and failure mechanisms [9,10,11,12]. Consistent with these findings, studies on bolted bamboo T-connections demonstrated that mortar infill significantly increases connection strength and stiffness, while natural variations in bamboo density and wall thickness remain important factors governing connection performance [14]. Similarly, investigations on bamboo-concrete composite connections showed that connection configuration governs the balance between strength, stiffness, and ductility, with combined mechanical connection systems providing improved load transfer and mitigating brittle failure compared with individual connection mechanisms [15]. Despite these advances, reviews continue to emphasize that the

anisotropic nature of bamboo, its hollow culm geometry, and variable node spacing introduce uncertainties in fastener performance, highlighting the need for experimental validation alongside theoretical models [13]. Investigations on laminated bamboo lumber and lightweight bamboo shear walls also confirm that connector configuration and cladding type influence lateral force distribution, racking capacity, and overall structural behavior [10,11,16,17]. Previous studies on bamboo-based shear wall systems have mainly evaluated full-scale wall performance under lateral loading, demonstrating that the interaction between bamboo framing, cement-based cladding, reinforcement, and connectors contributes to overall strength and stiffness. Under monotonic loading, these systems exhibit nonlinear behavior due to cement layer cracking, sheathing-frame slip, and connector deformation. Recent full-scale investigations of Composite Bamboo Shear Wall (CBSW) panels under monotonic and cyclic loading demonstrated adequate lateral resistance for both braced and unbraced configurations, with differences in stiffness, strength, ductility, and energy dissipation [18]. Complementary cyclic loading studies further indicate that connector behavior, sheathing interaction, and material characteristics influence hysteretic response, energy dissipation, and failure progression of bamboo shear wall systems [10,11,16]. These findings highlight that sheathing-to-framing connections are critical components governing shear transfer and the overall lateral response of CBFT and CBSW systems.

However, existing CBFT and CBSW studies, including recent full-scale experimental investigations of Composite Bamboo Shear Wall (CBSW) panels under monotonic and cyclic loading [18], have predominantly focused on the overall structural behavior of wall assemblies rather than the localized response of individual sheathing-to-framing connections. While full-scale wall testing provides valuable information on overall structural behavior, it does not isolate connection parameters such as nail quantity, cladding type, mortar confinement, and stud orientation. Variations in wall configurations, reinforcement systems, and loading protocols further limit understanding of connection-level behavior. Although nailed bamboo connections have been investigated in previous studies, limited research has examined the specific interaction between cement-based cladding systems, mortar confinement, nail configuration, and bamboo stud orientation within CBFT connection assemblies. Therefore, further experimental investigation at the connection level is required to quantify the mechanical behavior and failure mechanisms

governing nail-fastened CBFT connections, establish the influence of key connection parameters, and improve the understanding of their contribution to the overall structural performance of CBFT shear wall systems.

This study experimentally evaluates the monotonic shear behavior of nail-fastened sheathing-to-framing connections in CBFT at the subassembly level, assessing the effects of cladding type, nail quantity, mortar infill, and stud orientation on mechanical performance and failure mechanisms. The scope of this study is limited to connection-level response and does not represent the full structural behavior of CBFT shear wall systems.

2. RESEARCH SIGNIFICANCE

This study presents one of the first experimental investigations of nail-fastened sheathing-to-framing connections in Cement-Bamboo Frame Technology (CBFT), addressing the limited understanding of localized behavior in bamboo-based structural systems. Unlike previous studies focused primarily on full-wall performance, this research isolates the effects of nail configuration, cladding type, mortar confinement, and stud orientation under monotonic shear loading. The findings provide experimental data for improving CBFT connection design and supporting reliable, sustainable, and hazard-resilient bamboo construction systems.

3. METHODS

The overall experimental workflow is illustrated in Fig. 1. The framework summarizes the sequential stages of the study, including material characterization, specimen fabrication, monotonic shear testing, mechanical parameter extraction, and statistical analysis. This approach provides a structured basis for assessing the shear performance of nail-fastened sheathing-to-framing connections in Cement-Bamboo Frame Technology (CBFT) shear wall.

3.1 Experimental Variables and Specimen Configurations

3.1.1 Experimental Variables

The study examined the effects of cladding type, stud orientation, number of nails, and mortar infill on the shear performance of nail-fastened bamboo connections in Cement-Bamboo Frame systems. Rib lath and flattened bamboo panels were used as cladding materials, with studs oriented vertically or

horizontally, and connections fabricated using single or staggered nail configurations. Mortar infill was applied to selected specimens to evaluate its influence on stiffness and ultimate capacity. These configurations were selected because they represent existing CBFT construction practices and provide a basis for evaluating the influence of connection parameters on shear performance.

3.1.2 Specimen Configuration

Eight specimen types, Type 1 (T1) to Type 8 (T8), were fabricated to represent combinations of the selected experimental variables. Five replicates were prepared for each type ($n = 5$) for statistical evaluation. T1–T4 used rib lath cladding, while T5–T8 used flattened bamboo panels. Studs were oriented vertically or horizontally, and connections had one or three staggered nails. Mortar infill was applied to certain specimens to examine its effect on connection behavior. Table 1 summarizes the specimen configurations, including cladding, stud orientation, nail number, and mortar presence.

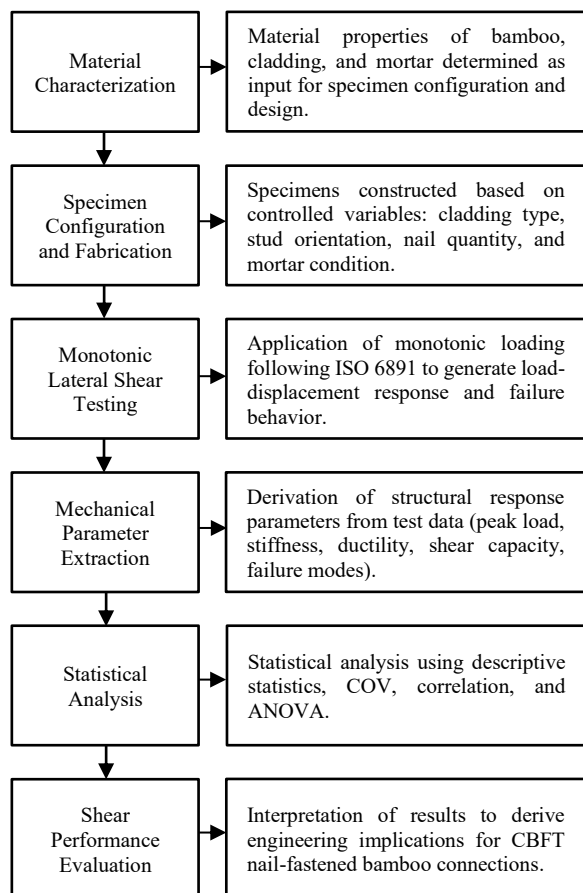


Fig.1 Methodological Framework of the Study

Table 1. Summary of Specimen Types and Cladding Materials

Specimen Type	Specimen ID	n	Cladding Material
TYPE 1	T1	5	Rib lath
TYPE 2	T2	5	Rib lath
TYPE 3	T3	5	Rib lath
TYPE 4	T4	5	Rib lath
TYPE 5	T5	5	Flattened bamboo
TYPE 6	T6	5	Flattened bamboo
TYPE 7	T7	5	Flattened bamboo
TYPE 8	T8	5	Flattened bamboo

Table 2. Summary of Specimen Configuration and Connection Parameters

Specimen ID	Stud Orientation	Number of Nails	Mortar Infill
T1	Vertical	1	No
T2	Vertical	1	Yes
T3	Vertical	3 (staggered)	Yes
T4	Horizontal	1	Yes
T5	Vertical	1	No
T6	Vertical	1	Yes
T7	Vertical	3 (staggered)	Yes
T8	Horizontal	1	Yes

3.1.3 Specimen Geometry and Connection Details

Bamboo studs were cut from mature culms, avoiding nodes and surface defects to minimize variability. Stud wall thickness ranged from 6.71 to 7.54 mm, while culm diameters ranged from 90.15 to 102.65 mm (see Section 3.2). Connections were made with common nails driven perpendicular to the stud-cladding interface, with spacing and stagger patterns defined for each specimen type. Cladding panels were fixed flush against the bamboo studs, and the specimens were designed to replicate standard CBFT sheathing-to-framing connections used in housing applications while remaining compatible with the testing apparatus.

Three specimen plans were used, as shown in Fig. 2, Fig. 3, and Fig. 4: (1) single-nail connections with vertical bamboo studs, (2) three staggered nails with vertical studs, and (3) single-nail connections with horizontal studs. Detailed dimensions for the studs and cladding panels are provided in the figures.

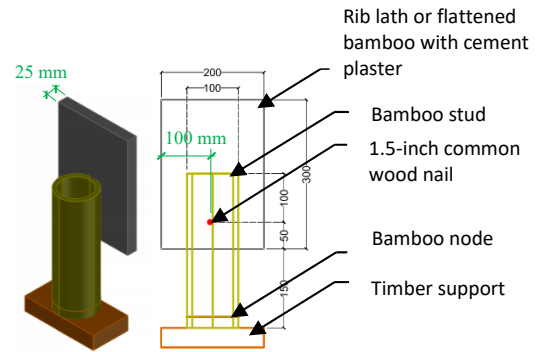


Fig. 2 One Nail Connection Plan with Vertical Bamboo Stud

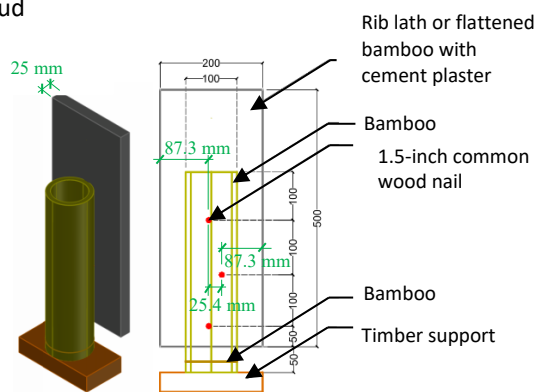


Fig. 3 Three-Nail Connection Plan with Vertical Bamboo Stud

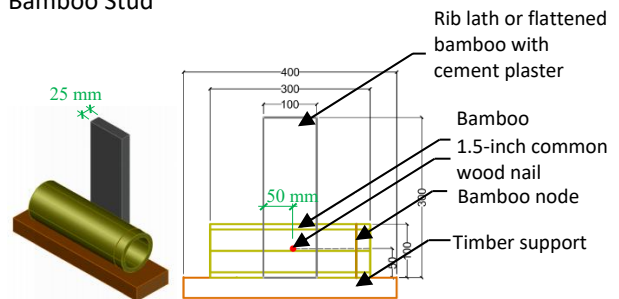


Fig. 4 One Nail Connection Plan with Horizontal Bamboo Stud

Specimen Type 1 (T1) served as the control specimen, consisting of rib lath cladding, vertical bamboo studs, a single nail, and no mortar infill. The remaining specimens were varied in terms of cladding type, mortar infill, number of nails, and stud orientation to evaluate their effects on shear behavior. Mortar-infilled specimens were sourced from wall corner regions, while non-mortar

specimens were taken from central regions. Additional configurations, including multiple nail arrangements and horizontal stud orientations, were tested to assess connection-level performance.

Table 3. Summary of Experimental Variables and Their Descriptions

Category	Variable	Levels / Description
Independent Variables	Cladding material	Rib lath; Flattened bamboo
	Mortar infill	With mortar; Without mortar
	Number of nails	One nail; Three staggered nails
	Stud orientation	Vertical; Horizontal
Dependent Variables	Peak load (Fmax)	Maximum load sustained during testing
	Yield load (Fy)	Determined following ISO/TR 21141:2022 Method A4
	Yield displacement (Vy)	Displacement corresponding to Fy
	Ultimate load (Fu)	Determined following ISO/TR 21141:2022
	Ultimate displacement (Vu)	Displacement corresponding to Fu
	Initial stiffness (k)	Calculated from the linear elastic region
	Ductility (μ)	Ratio of Vu to Vy
	Energy absorption (E)	Area under the load-displacement curve
	Failure modes	Observed connection failure mechanisms
Controlled Variables	Bamboo species	<i>Bambusa blumeana</i>
	Nail type	Common 1.5-inch nails (0.109-inch shank diameter)
	Mortar mix	1:3 cement-sand mixture
	Loading protocol	Displacement-controlled monotonic loading (ISO 6891)
	Loading rate	3 mm/min

Table 3 summarizes the independent, dependent, and controlled variables considered in the experimental program. The effects of cladding material, mortar infill, nail configuration, and stud orientation on the shear behavior of nail-fastened sheathing-to-framing connections were evaluated. To isolate these effects, all specimens were fabricated and tested using the same bamboo species, nail type, mortar mix, and loading protocol. The experimental program was designed using selected specimen configurations representative of practical CBFT construction rather than a complete full factorial arrangement of all possible variable combinations. Consequently, the results support comparisons among the tested configurations but do

not permit comprehensive evaluation of all higher-order interactions among the investigated variables.

3.2 Materials and Specimen Fabrication

This section describes the characterization of the constituent materials used in the experimental program, namely bamboo studs, cladding materials, nails, mortar, and plaster, followed by their preparation and incorporation into the test specimens. The physical and mechanical properties of each material were determined to ensure consistency among specimens and to provide baseline data for interpreting the experimental results.

3.2.1 Bamboo Stud Properties

Mature *Bambusa blumeana* poles, aged 3–5 years, were sourced from Batangas, Tarlac, and Dauin, Philippines, visually graded to exclude defects, chemically treated for insect and fungal resistance, and air-dried to improve material stability and reduce variability [19,20]. Consistent material selection was adopted because bamboo mechanical properties are influenced by environmental exposure, natural aging, and node distribution [21,22].

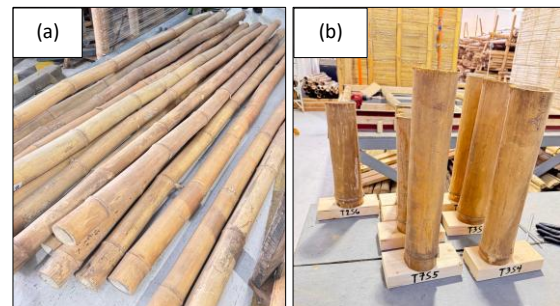


Fig. 5 One-Nail Connection Plan Showing Horizontal Bamboo Stud Preparation: (a) Treated Bamboo Poles, and (b) Cut Bamboo Studs.

Bamboo poles were cut into 300 mm and 400 mm lengths, and their wall thickness, culm diameter, moisture content, and density were measured in accordance with ISO 22157 [23]. Wall thickness ranged from 6.71–7.54 mm (CoV = 12.64–29.94%), culm diameter from 90.15–102.65 mm (CoV = 4.09–11.53%), moisture content from 6.36–7.68% (CoV = 1.55–7.01%), and density from 682.95–825.14 kg/m³, indicating low-to-moderate natural variability representative of structural bamboo used in CBFT applications.

Although density and moisture content were

measured to characterize the material consistency of the bamboo specimens, these properties were not used as normalization parameters. The objective of the study was to compare the mechanical response of practical CBFT connection configurations fabricated using representative construction materials rather than to establish material property-dependent relationships. The relatively narrow ranges of density and moisture content among the specimens were therefore considered sufficient to minimize their influence on the comparative evaluation of the investigated connection parameters.

Table 4. Bamboo Culm Wall Thickness of Test Specimens

Specimen Type	Wall Thickness, t (mm)	SD, t	CoV, t (%)
T1	7.28	0.92	12.64
T2	7.43	1.03	13.90
T3	7.54	0.99	13.16
T4	7.03	1.72	24.40
T5	6.71	1.39	20.66
T6	6.77	0.86	12.70
T7	7.32	2.19	29.94
T8	7.26	1.78	24.55

Table 5. Bamboo Culm Diameter of Test Specimens

Specimen Type	Culm Diameter, d (mm)	SD, d	CoV, d (%)
T1	97.55	10.13	10.38
T2	90.90	3.71	4.09
T3	102.65	9.13	8.89
T4	93.05	10.73	11.53
T5	102.40	10.40	10.16
T6	90.15	4.02	4.46
T7	95.00	8.11	8.54
T8	90.45	9.82	10.86

3.2.2 Cladding Material Properties

Commercially sourced rib lath panels and flattened bamboo sheets were used as the cladding materials, representing the two systems currently employed in Cement-Bamboo Frame Technology (CBFT) construction. Rib lath panels had a nominal thickness of 10 mm, while flattened bamboo panels ranged from 12 to 15 mm, depending on culm processing. All panels were visually inspected for surface defects and straightness, and their moisture content was controlled through oven-drying before

specimen fabrication.

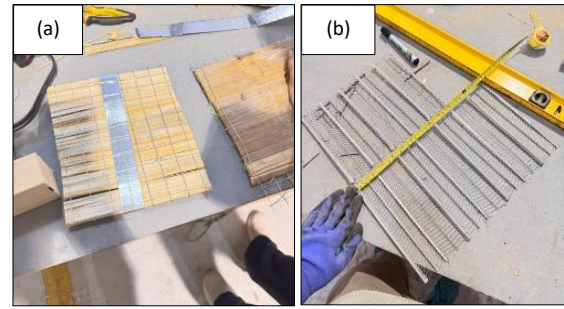


Fig. 6 Cladding Material Configurations for CBFT Specimens: (a) Flattened Bamboo Panel, and (b) Rib lath Panel.

3.2.3 Nail Properties

Common 1.5-inch nails (shank diameter 0.109 inch) were selected because they are the standard fasteners used in CBFT wall construction. Nails were inserted perpendicular to the stud-cladding interface, with staggered patterns applied in three-nail configurations to prevent splitting. Nail quality, straightness, and corrosion were inspected prior to fabrication to ensure uniform mechanical performance.

3.2.4 Mortar Properties

A 1:3 cement-sand mortar was used to infill the hollow bamboo culms of specimens T2, T3, T4, T6, T7, and T8, while T1 and T5 remained unfilled. Specimens were cured under laboratory conditions for seven days before testing.

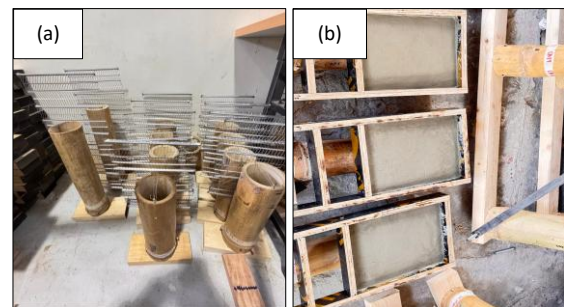


Fig. 7 CBFT Specimen Preparation and Curing: (a) Specimen with Rib Lath Cladding Attached, and (b) Specimens During Plaster and Mortar Curing.

The compressive strength of the mortar infill batches was measured to ensure proper quality control, following the procedures outlined in ASTM C109/C109M [25]. Seven-day wet curing produced strengths ranging from 12.98 MPa to 20.93 MPa with coefficients of variation between 2.13% and 12.00%. For specimens cured under dry conditions for 28

days (T7 and T8), the compressive strength increased to 20.86 MPa, reflecting the expected gain from extended curing. These results confirmed the suitability and uniformity of the mortar used in the experimental program.

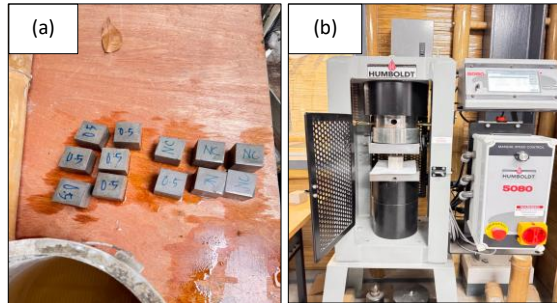


Fig. 8 Mortar Compressive Strength Testing Setup: (a) Mortar Samples Prepared for Testing, and (b) Compression Testing Machine.

3.2.5 Plaster Cement Properties

Plaster coatings were applied to all specimens (T1–T8) to simulate the finishing layer used in Cement-Bamboo Frame Technology (CBFT) wall construction. The compressive strength of the plaster cement was determined in accordance with ASTM C109/C109M [19]. After seven days of wet curing, compressive strengths ranged from 20.28 to 22.85 MPa, with coefficients of variation between 2.16% and 9.03%, indicating consistent material quality. The 28-day dry-cured plaster for T8 achieved a compressive strength of 22.21 MPa, demonstrating the expected strength gain with extended curing.

Standardized fabrication procedures were followed for all specimens. The same mortar mix proportion (1:3 cement-to-sand ratio), constituent materials, water addition, mixing procedure, plaster application method, and curing conditions were consistently applied throughout the study. Accordingly, the moisture content of the fresh cementitious mixtures was not treated as an experimental variable but was controlled through the standardized mix preparation to minimize variability among specimens. Nail placement and spacing were maintained according to the designed specimen configurations, while all specimens were fabricated following the same construction sequence. Bamboo moisture content, wall thickness, mortar compressive strength, and plaster compressive strength were characterized prior to testing to verify material consistency. These quality control measures ensured that the observed differences in mechanical behavior were primarily attributable to the investigated variables, namely cladding type, mortar infill, stud orientation, and nail

quantity, rather than inconsistencies in specimen fabrication or material preparation.

3.3 Monotonic Shear Testing

3.3.1 Testing Setup

Monotonic shear tests were conducted using an Autograph AG-X Plus universal testing machine. Relative displacement across the connection was measured using a single LVDT positioned to capture the relative slip between the cladding and bamboo framing at the connection interface, representing the primary deformation governing the connection response. Although additional displacement transducers could provide a more comprehensive description of specimen deformation, the selected measurement configuration was considered sufficient for evaluating the connection-level shear behavior investigated in this study. Load and displacement were recorded using the ALMEMO 710 data acquisition system and Trapezium X software. Failure progression was documented photographically.

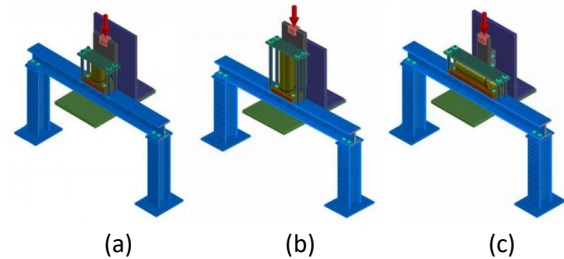


Fig. 9 SE Isometric Test Setup Showing Specimen Configurations: (a) One-Nail Vertical Bamboo Stud, (b) Three-Nail Vertical Bamboo Stud, and (c) One-Nail Horizontal Bamboo Stud.

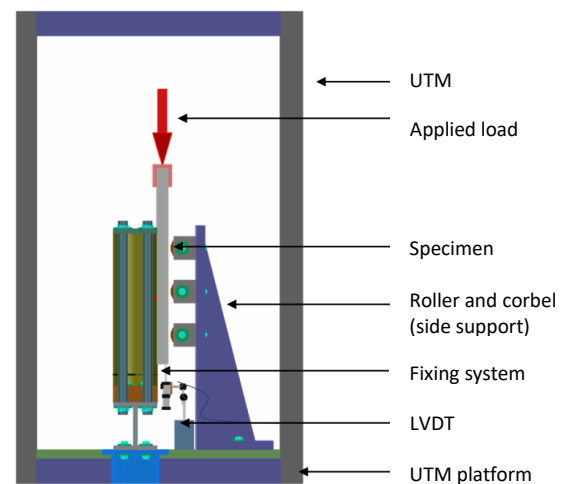


Fig. 10 Details of Test Setup

The specimen was mounted within a custom steel fixture designed to transfer load directly to the sheathing-to-framing connection while maintaining specimen alignment throughout testing. The bamboo framing member was rigidly secured to the lower fixture, whereas the cladding component was connected to the movable loading fixture attached to the UTM actuator. This configuration generated relative displacement between the cladding and bamboo framing, thereby inducing shear forces in the nailed connection representative of the load-transfer mechanism between sheathing and framing components in CBFT wall systems subjected to in-plane lateral loading. Alignment of the loading fixtures and specimen geometry reduced out-of-plane rotation and secondary bending effects, ensuring that the measured response was governed primarily by the in-plane shear behavior of the connection.

3.3.2 Loading Protocol

Specimens were installed in the Universal Testing Machine (UTM) using the custom steel fixture shown in Fig. 10 and aligned to produce in-plane shear at the nail-fastened sheathing-to-framing connection. Specimens were tested under displacement-controlled monotonic loading following ISO 6891 [24] at a constant loading rate of 3 mm/min. This loading rate represented the closest achievable constant displacement rate permitted by the available UTM while maintaining stable quasi-static monotonic loading. The same loading rate was applied consistently to all specimens to ensure valid comparisons among the tested configurations. Each test continued until connection failure, which was defined as the occurrence of a significant post-peak reduction in load-carrying capacity accompanied by one or more observable failure mechanisms, including bamboo splitting, nail pull-through, nail withdrawal, plaster cracking, cladding fracture, or connection separation. Failure modes were documented using high-resolution photographs for subsequent analysis.

Throughout the experimental program, several parameters were intentionally maintained constant to ensure that the observed variations in mechanical behavior resulted solely from the investigated variables. These controlled parameters included the bamboo species (*Bambusa blumeana*), specimen geometry, fastener type and dimensions, material sources, loading protocol, loading rate (3 mm/min), testing equipment, and data acquisition system. Material preparation and specimen fabrication were performed using standardized procedures, while mortar and plaster were prepared using their respective specified mix proportions and curing

protocols. Bamboo moisture content, wall thickness, mortar compressive strength, and plaster compressive strength were characterized prior to testing to verify material consistency. Maintaining these parameters constant enabled a direct comparison of the effects of cladding type, mortar infill, stud orientation, and nail quantity on the mechanical performance of the CBFT connections.

3.4 Experimental Data Processing and Observations

From the processed load-displacement data, key mechanical parameters were derived to characterize the shear behavior of the nail-fastened bamboo connections. The maximum load (F_{max}) was defined as the peak force recorded during testing.

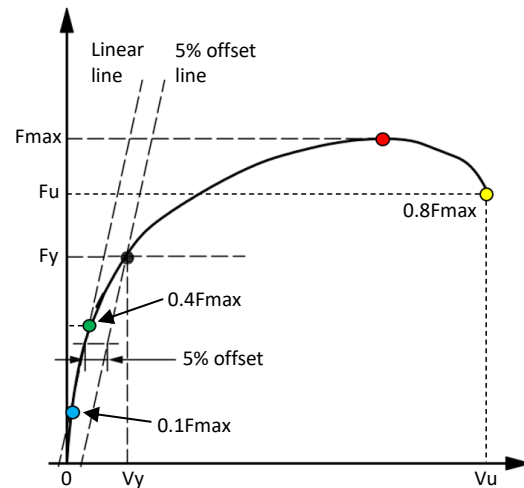


Fig. 11 Schematic Load-Displacement Curve with Identified Mechanical Parameters

The yield load (F_y) and corresponding displacement (V_y) were determined using Method A4 of ISO/TR 21141 [26] for dowel-type fasteners. A linear regression was fitted to the initial portion of the load-displacement curve; when nonlinearity was observed, the linear region between 10% and 40% of F_{max} was used. This line was then offset horizontally by 5% of the fastener diameter, and the intersection with the load-displacement curve was taken as the yield point.

The ultimate load (F_u) and corresponding displacement (V_u) were determined based on the post-peak response. For specimens exhibiting a sudden drop in load after reaching F_{max} , F_u was taken as the load immediately preceding the drop, satisfying $F_{max} \geq F_u \geq 0.8F_{max}$. For specimens with gradual post-peak softening, F_u was defined as $0.8F_{max}$ after the peak load. Accordingly, the relationship $F_y < F_u \leq F_{max}$ is maintained for all

specimens.

Initial stiffness (k) was calculated from the load–displacement response using the relative displacement measured by the LVDT, representing the local stiffness of the sheathing-to-framing connection rather than the global displacement of the UTM crosshead. A least-squares linear regression was fitted to the linear elastic region of each load–displacement curve, defined between 10% and 40% of F_{max} , and the slope of the fitted line was taken as the initial stiffness. The coefficient of determination (R^2) was evaluated for each regression to verify the quality of the linear fit.

$$k = \frac{\Delta F}{\Delta V} \quad (1)$$

Ductility (μ) was calculated as the ratio of ultimate displacement to yield displacement:

$$\mu = \frac{V_u}{V_y} \quad (2)$$

Energy absorption (E) was determined as the area under the load–displacement curve up to the ultimate displacement.

Qualitative observations, including bending, splitting, nail pull-through, cladding delamination, and plaster cracking, were recorded, with high-resolution photographs documenting failure patterns.

3.5 Statistical Analysis

A two-way ANOVA was used to examine how cladding type, stud orientation, nail quantity, and mortar infill affected the shear performance of the connections. Data normality was checked with histograms, normal probability plots, and the Shapiro-Wilk test, while homogeneity of variance was confirmed to meet ANOVA assumptions. For each group, mean, standard deviation, and coefficient of variation were calculated. Effects were considered statistically significant at $\alpha = 0.05$, with p -values below 0.05 indicating a meaningful influence of the factors or their interactions. Energy absorption was excluded from the ANOVA due to its cumulative nature and sensitivity to post-peak variability, which may introduce additional dispersion in the results.

4. RESULTS AND DISCUSSION

This section presents the monotonic shear test results of nail-fastened sheathing-to-framing connections in CBFT, focusing on failure modes, load capacity, stiffness, ductility, and energy absorption.

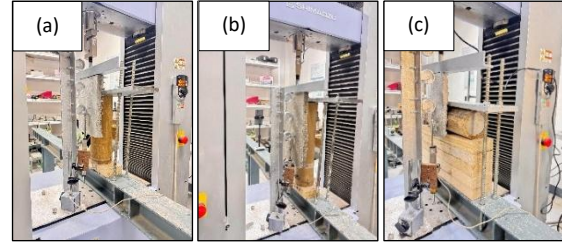


Fig. 12 Experimental Test Setups for (a) Vertical Single-Nail, (b) Three-Staggered Nail Connections, and (c) Horizontal Single-Nail.

4.1 Load-Displacement Behavior

The representative load–displacement curves clearly reflect the influence of cladding type, nail quantity, mortar infill, and stud orientation on connection behavior. Rib lath specimens show distinct patterns: Type 1, with a single vertical nail and no mortar, exhibits moderate post-peak softening, corresponding to nail pull-out from the bamboo stud while the cladding remains intact. Type 2, with mortar, reaches its peak quickly but fails abruptly, reflecting nail bending and rib lath tearing. Type 3, with multiple nails and mortar, maintains a smooth post-peak decline, indicating effective load sharing and combined nail and cladding failure. Type 4, a horizontal rib lath with mortar, drops sharply after peak, consistent with nail bending and partial cladding detachment. Flattened bamboo specimens behave differently: Type 5, without mortar, shows an extended post-peak tail due to pull-out with minor nail bending. Types 6 and 8, with mortar, experience sudden drops linked to nail bending, cladding detachment, and localized tearing, with horizontal orientation further reducing residual load. Type 7, with multiple vertical nails and mortar, combines a high peak with sustained post-peak load, reflecting progressive bending and crushing across nails and cladding. Overall, the curve characteristics correspond with the observed failure modes, indicating that mortar improves post-yield resistance, multiple nails enhance load sharing, and rib lath provides more effective load transfer through improved mechanical interlocking with plaster.

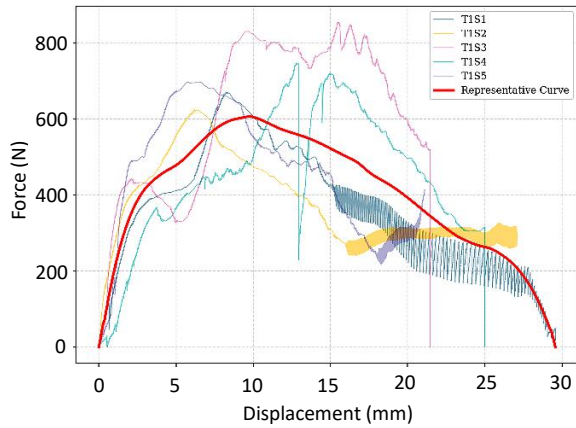


Fig. 13 Force–displacement curves of Type 1 (T1) specimens with rib lath cladding, vertical studs, a single nail, and no mortar infill.

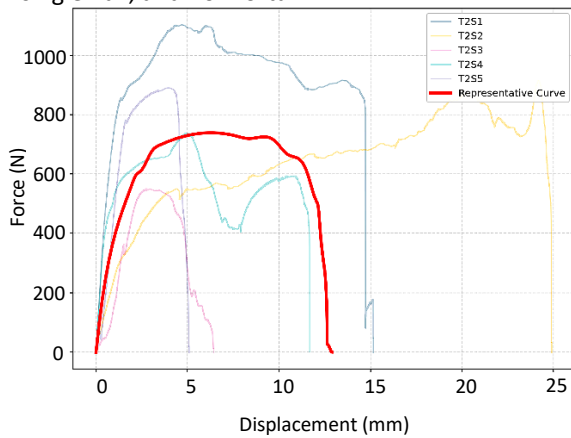


Fig. 14 Force–displacement curves of Type 2 (T2) specimens with rib lath cladding, vertical studs, a single nail, and mortar infill.

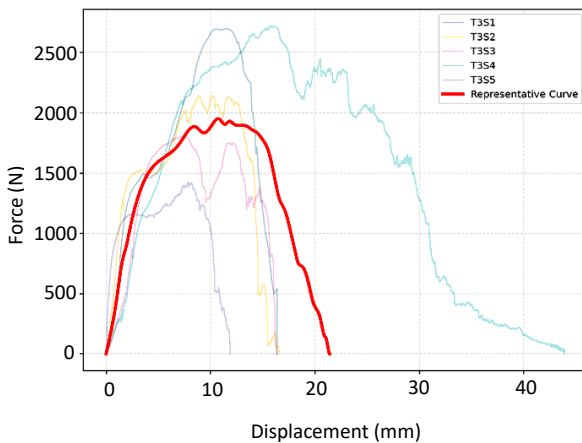


Fig. 15 Force–displacement curves of Type 3 (T3) specimens with rib lath cladding, vertical studs, three staggered nails, and mortar infill.

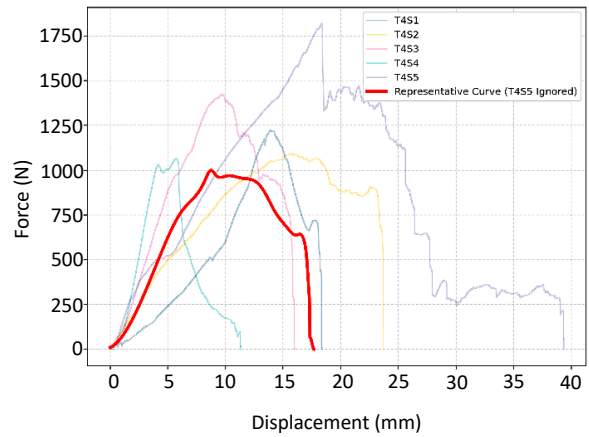


Fig. 16 Force–displacement curves of Type 4 (T4) specimens with rib lath cladding, horizontal studs, a single nail, and mortar infill.

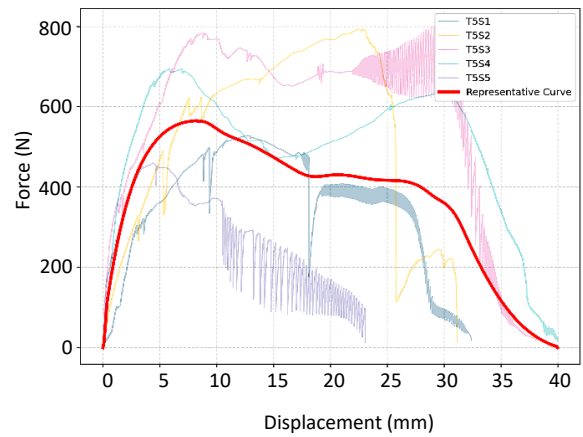


Fig. 17 Force–displacement curves of Type 5 (T5) specimens with flattened bamboo cladding, vertical studs, a single nail, and no mortar infill.

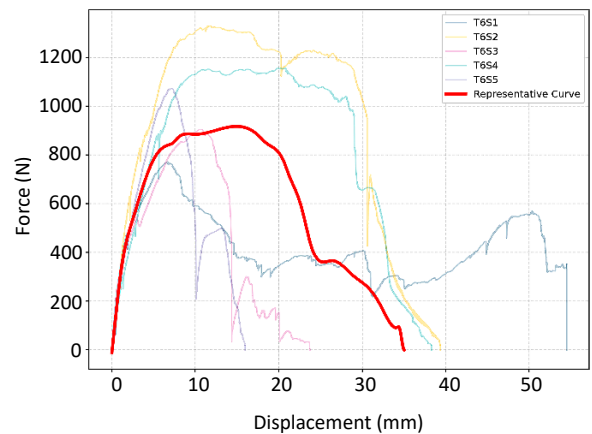


Fig. 18 Force–displacement curves of Type 6 (T6) specimens with flattened bamboo cladding, vertical studs, a single nail, and mortar infill.

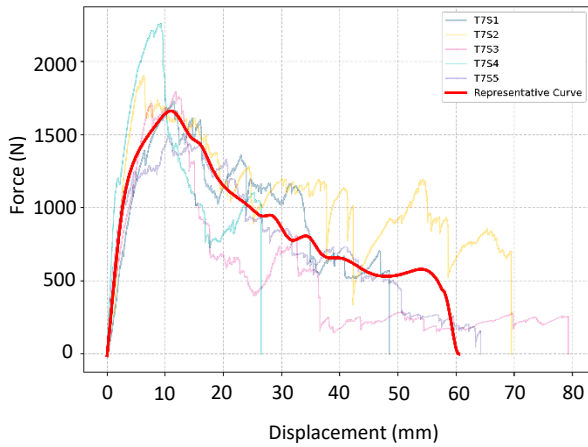


Fig. 19 Force–displacement curves of Type 7 (T7) specimens with flattened bamboo cladding, vertical studs, three staggered nails, and mortar infill.

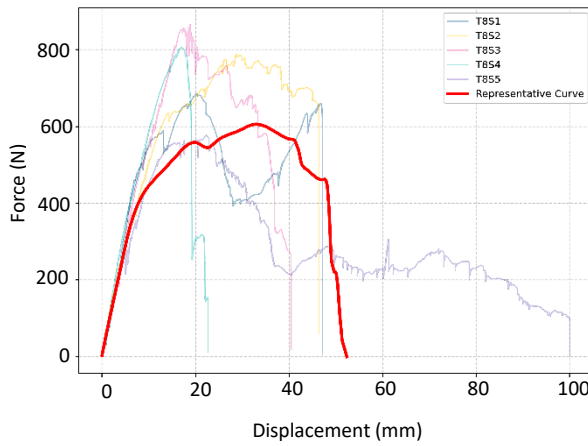


Fig. 20 Force–displacement curves of Type 8 (T8) specimens with flattened bamboo cladding, horizontal studs, a single nail, and mortar infill.

4.2 Failure Mode Analysis

The observed failure modes demonstrate the effects of cladding type, mortar infill, nail quantity, and stud orientation on connection behavior. All specimens initially exhibited bamboo embedment at yield due to localized bearing deformation at the fastener–bamboo interface. For rib lath specimens (T1–T4), T1 primarily failed through nail pull-out, while mortar-infilled specimens (T2–T4) failed through nail bending and rib lath tearing. Nail bending indicated dowel-type fastener deformation during shear transfer, whereas rib lath tearing resulted from localized bearing and tensile failure around the fastener. The three-nail configuration (T3) improved load sharing, while T4 exhibited partial cladding detachment due to less favorable stress distribution. The mechanical interlock between rib lath and plaster enhanced load transfer by distributing stresses over a larger area, delaying

bearing failure and fastener withdrawal.

Flattened bamboo specimens (T5–T8) exhibited similar initial embedment behavior, but their post-yield failures were more complex. T5 (1 nail, no mortar) failed primarily through nail pull-out, while T6–T8 (with mortar) showed nail bending, cladding crushing, and localized tearing. Cladding crushing represents localized compressive bearing failure beneath the fastener, while localized tearing indicates progressive fracture of the bamboo fibers surrounding the nail as the connection continued to deform after yielding. T7 (3 nails, vertical) displayed combined nail bending and cladding crushing due to improved load sharing, whereas horizontal studs (T8) experienced nail bending with localized stud and cladding damage. Compared with rib lath specimens, flattened bamboo exhibited weaker interaction with the plaster layer due to its relatively smooth and less mechanically interlocked surface. Unlike rib lath, which contains an open mesh structure that allows plaster penetration and mechanical keying, flattened bamboo relies primarily on surface adhesion and friction between the plaster and bamboo surface. The limited surface roughness and reduced mechanical interlock of flattened bamboo may promote earlier separation between the cladding layer and the plaster, leading to reduced load transfer efficiency and greater post-yield deformation.

Table 6. Summary of Critical Failure Modes for Each Specimen

Specimen	Configuration	Critical Failure Mode
T1	Rib lath, vertical, 1 nail, no mortar	Nail pull-out (from bamboo; cladding intact)
T2	Rib lath, vertical, 1 nail, with mortar	Nail bending & rib lath tearing
T3	Rib lath, vertical, 3 nails, with mortar	Nails bending & rib lath tearing
T4	Rib lath, horizontal, 1 nail, with mortar	Nail bending & rib lath tearing
T5	Flattened bamboo, vertical, 1 nail, no mortar	Nail pull-out (from bamboo; sheet intact)
T6	Flattened bamboo, vertical, 1 nail, with mortar	Nail bending & cladding detachment
T7	Flattened bamboo, vertical, 3 nails, with mortar	Nails bending & cladding crushing; sheet pulled
T8	Flattened bamboo, horizontal, 1 nail, with mortar	Nail bending & cladding detachment

Therefore, the difference in bond performance between the two cladding types is attributed to

variations in surface texture, mechanical interlocking capacity, and the nature of plaster-cladding interaction.

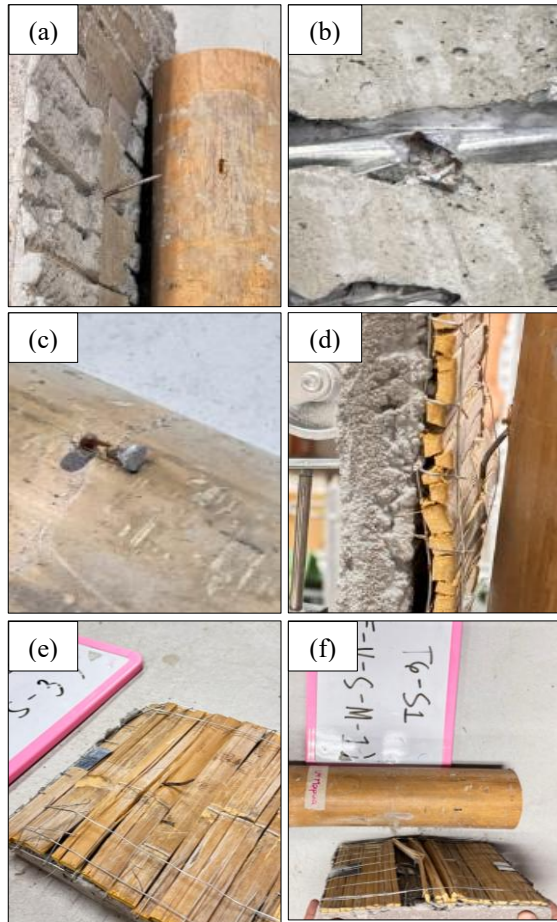


Fig. 21 Observed Failure Modes of Nail-Fastened CBFT Connections: (a) Nail Pull-Out From Bamboo Stud, (b) Rib Lath Tear-Out with Nail Detachment, (c) Nail Bending with Embedment in Bamboo Stud, (d) Combination of Nail Bending and Pull-Out During Testing, (e) Nail Bending and Pull-Out from Bamboo Stud After Testing, (f) Nail Detachment and Flattened Bamboo Crushing.

Overall, mortar infill shifted failure from fastener withdrawal toward nail bending and cladding damage by improving confinement and load transfer. Multiple nails enhanced load sharing, while rib lath improved stress redistribution through stronger interaction with the plaster layer. These observations are consistent with dowel-type connection behavior governed by fastener deformation, bearing resistance, and cladding integrity. The governing failure modes were generally consistent among the five replicates within each specimen configuration, although minor variations in the extent of bamboo splitting, cladding

damage, and nail deformation were observed due to the inherent variability of natural bamboo. Minor variations were attributed to natural bamboo variability but did not change the dominant failure mechanisms.

4.3 Mechanical Performance of Connections

The mechanical performance of the nail-fastened CBFT connections was influenced by cladding type, nail quantity, stud orientation, and mortar infill.

Table 7. Yield and Ultimate Load Capacities of the Tested Specimens

Specimen ID	Maximum Load (N)	Yield Load (N)	Ultimate Load (N)
T1	714.21 ± 79.88	425.32 ± 44.37	604.00 ± 104.58
	838.72 ± 207.00	590.11 ± 138.88	670.98 ± 165.60
T2	2158.30 ± 564.25	1418.38 ± 183.17	1726.64 ± 451.40
	1324.66 ± 310.51	1115.39 ± 274.63	1192.19 ± 279.45
T3	651.87 ± 151.05	546.83 ± 114.34	586.68 ± 135.94
	1047.72 ± 217.10	884.24 ± 175.07	942.95 ± 195.39
T4	1833.04 ± 284.74	1496.21 ± 301.09	1649.74 ± 256.27
	744.71 ± 114.05	611.36 ± 114.07	670.23 ± 102.64

Table 8. Summary of Stiffness, Ductility, and Energy Absorption of Specimens

Specimen ID	Initial Stiffness (N/mm)	Ductility	Energy Absorbed (N-mm)
T1	251.69 ± 56.00	3.75 ± 0.95	10991.52 ± 1305.06
	585.53 ± 128.85	2.81 ± 0.82	2897.54 ± 885.53
T2	839.87 ± 184.52	3.71 ± 0.96	22189.05 ± 6126.37
	158.16 ± 15.29	1.25 ± 0.18	9458.74 ± 2824.99
T3	236.75 ± 51.48	2.22 ± 0.63	7188.67 ± 1769.49
	263.04 ± 68.55	1.63 ± 0.47	11273.32 ± 3004.82
T4	439.59 ± 92.24	1.80 ± 0.52	50272.26 ± 15402.33
	62.62 ± 7.91	1.80 ± 0.48	18562.26 ± 5281.19

Among the rib lath specimens (T1–T4), T3 exhibited the highest yield load, ultimate load, and initial stiffness, whereas T4 showed lower stiffness because of the horizontal stud orientation. The superior performance of T3 is attributed to the combined effects of mortar confinement and three

staggered nails, which improved load sharing, reduced stress concentrations around individual fasteners, and enhanced the mechanical interlock between the rib lath and plaster. Conversely, the horizontal orientation promoted less favorable stress transfer, resulting in reduced post-yield load-carrying efficiency.

For the flattened bamboo specimens (T5 to T8), single-nail configurations generally exhibited lower strength than the corresponding rib lath specimens. Mortar infill improved the load-carrying capacity by providing confinement around the nail and enhancing load transfer between the cladding and bamboo stud, thereby reducing premature nail withdrawal. The three-nail specimen (T7) exhibited the highest ultimate load (1649.74 N) and energy absorption (50,272 N-mm) among the flattened bamboo specimens, indicating improved load sharing and delayed localized failure. In contrast, the horizontal specimen (T8) exhibited the lowest stiffness, suggesting that the horizontal stud orientation resulted in less efficient stress transfer and greater connection slip during loading.

The observed progression from localized bearing (embedment) deformation to nail bending or pull-out is generally consistent with the findings of Malkowska et al. [6], who reported that laterally loaded nailed bamboo connections initially exhibit bearing deformation at yield before developing ultimate failure through localized mechanisms such as nail withdrawal, splitting, or bearing failure.

Overall, mortar infill, increased nail quantity, and vertical stud orientation improved the strength, stiffness, and energy absorption of the tested connections. Rib lath generally exhibited greater stiffness than flattened bamboo because its open mesh geometry provided stronger mechanical interlocking with the plaster, resulting in more efficient stress transfer across the sheathing-to-framing interface. Conversely, the relatively smooth surface of flattened bamboo relied primarily on surface adhesion, leading to greater post-yield deformation and reduced connection stiffness. These trends are consistent with the observed failure modes, where improved confinement and load distribution shifted the response from fastener withdrawal toward nail bending and localized cladding damage.

The inclusion of mortar infill enhances load transfer in CBFT nail connections by providing internal confinement within the hollow bamboo culms, increasing the bearing resistance around the nail, and reducing premature nail withdrawal. The non-mortar specimens (T1 and T5) primarily failed through nail pull-out from the bamboo stud, indicating limited anchorage and reduced resistance

after yielding.

Table 9. Strength and Energy Absorption per Nail for Tested Specimens

Specimen ID	Nail Quantity	Strength per Nail (N)	Energy per Nail (N-mm)
T1	1	604.00 ± 104.58	10991.52 ± 1305.06
T2	1	670.98 ± 165.60	2897.54 ± 885.53
T3	3	575.55 ± 150.47	7396.35 ± 2042.12
T4	1	1192.19 ± 279.45	9458.74 ± 2824.99
T5	1	586.68 ± 135.94	7188.67 ± 1769.49
T6	1	942.95 ± 195.39	11273.32 ± 3004.82
T7	3	549.91 ± 85.42	16757.42 ± 5134.11
T8	1	670.23 ± 102.64	18562.26 ± 5281.19

In contrast, the mortar-infilled specimens (T2, T3, T4, T6, T7, and T8) exhibited nail bending while remaining engaged with the bamboo stud, demonstrating that the mortar contributed to improved confinement and more effective force transfer between the nail, bamboo stud, and cladding system. The normalized strength per nail, calculated as the ultimate load divided by the number of nails, indicates that although multi-nail configurations may have lower strength per individual fastener, the additional fasteners promote better load distribution within the connection. These results indicate that mortar confinement shifts the governing failure mode from nail pull-out to nail bending while improving load transfer between the nail, bamboo stud, and cladding, thereby enhancing the overall mechanical performance of the connection.

4.4 Two-Way ANOVA Analysis

Separate two-way ANOVA analyses were performed instead of a full factorial ANOVA because the experimental program was designed to evaluate practical Cement-Bamboo Frame Technology (CBFT) construction configurations rather than a complete factorial combination of all investigated variables. The selected specimen configurations did not include every possible combination of cladding type, mortar infill, nail quantity, and stud orientation; therefore, separate two-way ANOVA analyses were conducted to evaluate the main effects and interactions of comparable factors. Prior to performing ANOVA, the normality of each dependent variable within specimen groups was

assessed using graphical methods (histograms and normal probability plots) and the Shapiro-Wilk test to ensure approximate normal distribution. Descriptive statistics, including mean, standard deviation, and coefficient of variation, were calculated, and outliers were reviewed based on engineering judgment. Homogeneity of variance across groups was also checked to satisfy ANOVA assumptions. These steps ensured that the parametric requirements were reasonably met, allowing reliable interpretation of ANOVA outputs, including sum of squares, mean squares, F-statistics, degrees of freedom, and p-values, which quantify the significance of each factor and their interactions.

4.4.1 Effect of Cladding and Mortar Infill on Mechanical Properties

The two-way ANOVA results indicate that both cladding type and mortar infill significantly influenced stiffness and yield load, with p-values below 0.001 for individual factors and their interaction.

Table 10. Two-way ANOVA Results for the Effects of Cladding and Mortar Infill on Mechanical Properties

Parameter	Factor	F(1,16)	p-value
Stiffness	Cladding	21.017	0.000305
	Mortar Infill	23.938	0.000163
	Interaction	17.459	0.00071
Yield Load	Cladding	13.293	0.002177
	Mortar Infill	19.407	0.000442
	Interaction	2.293	0.149479
Ultimate Load	Cladding	3.412	0.083297
	Mortar Infill	9.426	0.007322
	Interaction	4.404	0.052085
Ductility	Cladding	16.665	0.000868
	Mortar Infill	5.318	0.034825
	Interaction	0.294	0.595352

Rib lath connections exhibited higher stiffness and yield capacity than flattened bamboo, consistent with their more compact structure and improved adhesion to plaster. Mortar infill also enhanced stiffness and yield load by providing additional confinement and load transfer, reducing localized deformation. The interaction effect was significant for stiffness but not for yield load or ultimate load, suggesting that while combined cladding and mortar improves rigidity. The interaction effect was significant only for stiffness, whereas ultimate load

was influenced primarily by mortar infill rather than by the combined effect of cladding and mortar. Ductility was affected by both cladding and mortar, with flattened bamboo showing higher post-yield deformation, whereas mortar reduced ductility by constraining movement.

4.4.2 Effect of Cladding and Number of Nails on Mechanical Properties

Increasing the number of nails significantly improved yield and ultimate loads as well as stiffness ($p < 0.01$), reflecting enhanced load sharing and reduced localized fastener stress.

Table 11. Two-Way ANOVA Results for the Effects of Cladding and Nail Quantity on Mechanical Properties

Parameter	Factor	F(1,16)	p-value
Stiffness	Cladding	40.903	0.000009
	Nail Quantity	14.538	0.00153
	Interaction	0.474	0.501086
Yield Load	Cladding	3.972	0.063589
	Nail Quantity	59.558	0.000001
	Interaction	1.343	0.263462
Ultimate Load	Cladding	0.568	0.462057
	Nail Quantity	46.357	0.000004
	Interaction	1.816	0.196514
Ductility	Cladding	22.893	0.000203
	Nail Quantity	2.725	0.118302
	Interaction	1.306	0.269956

Cladding type significantly affected stiffness and ductility, whereas its effect on yield load was not statistically significant ($p = 0.0636$). Rib lath generally exhibited higher stiffness than flattened bamboo but lower ductility under multi-nail configurations. The interaction between cladding and nail quantity was generally non-significant, indicating that the positive effects of increasing nail number apply similarly to both cladding types. Ultimate load was particularly sensitive to nail quantity ($p < 0.001$), confirming that adding nails effectively increases load-bearing capacity even when cladding type alone does not dominate ultimate strength.

4.4.3 Effect of Cladding and Stud Orientation on Mechanical Properties

Stiffness was significantly influenced by both cladding type and stud orientation, and their interaction was also significant ($p = 0.003$), indicating that the stiffest response was obtained from rib lath specimens with vertical stud orientation.

Table 12. Two-Way ANOVA Results for the Effects of Cladding and Stud Orientation on Mechanical Properties

Parameter	Factor	F(1,16)	p-value
Stiffness	Cladding	40.454	0.000009
	Stud Orientation	91.235	0.00000002
	Interaction	11.923	0.003273
Yield Load	Cladding	1.592	0.225114
	Stud Orientation	2.302	0.148711
	Interaction	23.02	0.000197
Ultimate Load	Cladding	2.026	0.173827
	Stud Orientation	2.002	0.17627
	Interaction	20.434	0.000349
Ductility	Cladding	1.676	0.213776
	Stud Orientation	8.39	0.010515
	Interaction	12.856	0.002474

This finding demonstrates that the influence of stud orientation depends on the cladding system used, with the combination of rib lath and vertically oriented studs providing the most efficient load-transfer mechanism during the initial loading stage. Yield and ultimate loads were not individually affected by cladding or orientation, but their interaction was significant, highlighting the importance of joint configuration in determining strength. Ductility was influenced by stud orientation and its interaction with cladding. Horizontal studs generally reduced stiffness and promoted localized tearing, particularly in flattened bamboo connections. This behavior can be attributed to the altered load-transfer path created by the horizontal framing arrangement, which increases local member rotation and nail embedment deformation before the connection can fully resist the applied load. Consequently, greater connection slip occurs during the initial loading stage, reducing the initial stiffness. In contrast, vertically oriented studs provide a more direct load path that limits local deformation and allows the nail connections to engage more effectively, thereby increasing the structural stiffness. However, stud orientation alone did not significantly affect yield load or ultimate load; rather, the significant interaction between cladding type and stud orientation indicates that their combined effect governs connection strength. The influence of cladding on stiffness is associated with its contribution to the composite action of the connection. Rib lath embedded in plaster forms a relatively rigid reinforcement layer that improves stress distribution and restrains localized deformation around the fasteners, thereby increasing the resistance to initial displacement.

Conversely, flattened bamboo with chicken wire is comparatively more compliant and permits greater local deformation prior to full engagement of the nail connections, resulting in lower initial stiffness. Because the interaction between cladding type and stud orientation was statistically significant ($p = 0.003$), these factors should not be considered independently. Instead, the stiffness of the CBFT connection is governed by the combined behavior of the cladding system, bamboo framing orientation, and nail load-transfer mechanism.

Energy absorption was excluded from the ANOVA due to its derived nature and sensitivity to measurement variability. Nonetheless, the observed trends in energy dissipation mirrored the statistical findings for yield load, stiffness, and ductility, reinforcing the role of cladding, nail quantity, mortar, and stud orientation in defining connection performance.

Although the monotonic loading protocol adopted in this study provides a reliable basis for evaluating the relative effects of cladding type, mortar infill, nail configuration, and stud orientation on the mechanical behavior of CBFT nail connections, the results should be interpreted within the scope of monotonic loading conditions. The measured strength, stiffness, ductility, energy absorption, and failure modes establish the fundamental connection behavior and provide baseline data for comparing different CBFT connection configurations. However, monotonic loading does not capture the repeated load reversals, cumulative damage, stiffness degradation, or hysteretic energy dissipation that may occur under earthquake or typhoon-induced lateral loading. Consequently, while the present findings are valuable for identifying mechanically superior connection configurations, additional cyclic loading and full-scale wall tests are recommended to further evaluate the performance of CBFT systems subjected to realistic dynamic loading conditions. The results should therefore be interpreted as representative of connection-level behavior only and should not be considered direct evidence of the structural reliability, disaster resilience, or wall-level performance of complete CBFT systems. Accordingly, the connection configurations identified in this study are intended primarily for the preliminary screening of promising CBFT connection details and to guide future cyclic and full-scale wall investigations, rather than to serve as direct design recommendations for structural applications.

5. CONCLUSION

Cement-Bamboo Frame Technology (CBFT) is a

sustainable bamboo-based wall system in which sheathing-to-framing connections play an important role in transferring lateral loads. This study evaluated the monotonic shear behavior of nail-fastened CBFT sheathing-to-framing connections using rib lath and flattened bamboo cladding. The effects of cladding type, nail quantity, mortar infill, and stud orientation were investigated through load–displacement behavior, failure mode observations, mechanical properties, and statistical analysis. The principal findings are summarized as follows:

- **Effect of Nail Quantity and Mortar Infill on Stiffness and Load Capacity:** Vertical specimens with multiple nails and mortar infill exhibited the highest stiffness and load-bearing capacity. The best-performing configuration, T3 (rib lath, 3 nails, with mortar), achieved an initial stiffness of 839.87 N/mm, a yield load of 1418.38 N, and an ultimate load of 1726.64 N. These results demonstrate that mortar confinement and increased nail quantity enhanced load transfer, reduced nail pull-out, and improved connection stiffness and strength.
- **Impact of Mortar Infill on Failure Mode:** Specimens without mortar (T1 and T5) failed primarily by nail pull-out from the bamboo, whereas mortar-infilled specimens predominantly exhibited nail bending accompanied by rib lath tearing, cladding detachment, or cladding crushing. These observations indicate that mortar confinement improved load transfer by shifting the governing failure mechanism from nail withdrawal to nail bending, thereby enhancing connection performance.
- **Effect of Cladding Type on Mechanical Performance:** Rib lath connections generally exhibited higher stiffness and load-bearing capacity than flattened bamboo connections, although certain flattened bamboo configurations with mortar infill achieved comparable strength values. Their superior stiffness is attributed to their stronger mechanical interlock with the plaster layer, whereas flattened bamboo generally exhibited greater post-yield deformation.
- **Influence of Stud Orientation:** Horizontal studs reduced stiffness and altered failure behavior. T4 (rib lath, horizontal, 1 nail, with mortar) had a stiffness of 158.16 N/mm and an ultimate load of 1192.19 N, compared to vertical T2

(rib lath, 1 nail, with mortar), which reached a higher stiffness (585.53 N/mm) but a lower ultimate load (670.98 N). Horizontal orientation also altered the failure behavior of flattened bamboo connections, with T8 (flattened bamboo, horizontal stud, single nail, with mortar infill) exhibiting nail bending and cladding detachment, highlighting the importance of stud orientation for predictable connection performance.

- **Ductility and Energy Absorption:** Single-nail, non-mortar specimens (T1 and T5) exhibited higher ductility (3.75 and 2.22, respectively), allowing greater deformation before failure. Multi-nail, mortar-infilled specimens exhibited stiffer behavior, while T7 (flattened bamboo, 3 nails, vertical, with mortar) achieved the highest energy absorption (50,272.26 N·mm), demonstrating the combined benefits of mortar confinement and multiple fasteners.
- **Statistical Validation of Mechanical Behavior:** Two-way ANOVA confirmed that stiffness was significantly influenced by cladding type, mortar infill, nail quantity, and stud orientation, while yield and ultimate loads were primarily affected by nail quantity and specific factor interactions. Ductility was influenced by stud orientation and its interaction with cladding. Mortar infill played a critical role in modifying failure modes by shifting the governing mechanism from nail pull-out toward nail bending and cladding damage.
- **Overall Connection Performance:** The experimental results demonstrate that cladding type, nail quantity, mortar infill, and stud orientation collectively influence the stiffness, strength, ductility, and failure behavior of nail-fastened CBFT connections under monotonic loading. Mortar infill improved load transfer by shifting failure from nail pull-out to nail bending, while rib lath cladding and vertical studs generally provided the highest stiffness and strength.

Overall, the monotonic shear behavior of nail-fastened CBFT connections was influenced by the combined effects of cladding type, nail quantity, mortar infill, and stud orientation. Within the scope of the connection-level tests conducted in this study, these parameters affected stiffness, strength, ductility, energy absorption, and failure mode. The findings provide experimental data that can support future studies on the development and evaluation of

CBFT connection systems and full-scale wall assemblies.

Limitations of this study include the use of monotonic loading only, testing at the connection level rather than full-wall assemblies, the consideration of a limited range of nail sizes and arrangements, and the inherent variability of natural bamboo despite material characterization. Although bamboo moisture content, wall thickness, and mechanical properties were characterized to improve material consistency, natural variations in bamboo geometry, fiber distribution, and localized defects cannot be completely eliminated. Consequently, the findings should be interpreted as representative of connection-level behavior and may not fully capture the cyclic loading effects, cumulative damage, stiffness degradation, hysteretic energy dissipation, and system-level interactions that occur in complete CBFT wall systems subjected to seismic or typhoon-induced loading. Furthermore, the water content of the cementitious mixtures was controlled through standardized material preparation and curing procedures and was therefore not treated as an experimental variable. Although variations in water content can influence mortar hydration, bond development, and compressive strength, these effects were minimized through the consistent fabrication procedures adopted throughout the study and were not expected to influence the comparative evaluation of the investigated variables.

Future work should investigate cyclic and seismic loading effects on multi-nail CBFT connections, explore a wider range of fastener types and sizes, and extend testing to full-wall panels to capture system-level interactions. Additionally, long-term durability under varying environmental conditions and evaluation of energy absorption metrics in statistical analyses could further inform optimized connection design. Based on the present findings, the use of mortar infill, rib lath cladding, vertical studs, and appropriate nail configurations is recommended to improve the stiffness, strength, and reliability of CBFT connections.

6. ACKNOWLEDGMENTS

The authors sincerely acknowledge the guidance and valuable feedback provided by Dr. Cris Edward F. Monjardin, Dr. Roneh Glenn D. Libre Jr., and Dr. Kevin Paolo V. Robles, which significantly contributed to the improvement of this study. The Engineering Research and Development for Technology (ERDT) Program is also gratefully acknowledged for its support in the completion of this research.

Special appreciation is extended to BASE Bahay Foundation, Inc. for providing access to materials, technical assistance, and other resources essential for the conduct of the experimental program. Their support made the implementation of this study possible.

The authors also express gratitude to the laboratory staff and colleagues who assisted in specimen preparation, data collection, and testing, ensuring the accuracy and smooth execution of the experimental work.

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