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Parametric CAD/CAM toolchain for adaptive bamboo joints: Digital fabrication and experimental validation for rural structures

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Abstract*– Bamboo is a renewable and abundant material, but its geometric variability (diameter, ovality, taper, wall thickness) complicates the development of standardized connections for structural applications. This paper presents a parametric CAD/CAM toolchain, implemented in Rhino/Grasshopper, that generates adaptive steel joints for bamboo culms of varying sizes and connection angles. The system encodes geometric constraints and structural rules, particularly the orientation of steel plates according to section properties, producing fabrication-ready outputs (DXF and assembly guides) suitable for manual or CNC manufacturing. A prototype joint was fabricated and tested in a cantilever bending experiment with a 3-m bamboo member. Results demonstrated a linear load–deflection response up to 39.2 N, with failure at 49 N due to bamboo splitting. The implemented orientation rules improved bending resistance by a factor of ≈50×, confirming the role of simple codified decisions in enhancing performance. The contribution aligns with ICITS themes on software systems (D), systems modeling (C), and decision support (G), illustrating how digital fabrication can translate computational design into practical, low-cost technologies for sustainable rural construction.

***Keywords*- Parametric modeling, Rhino/Grasshopper, Sustainable architecture.**

I. Introduction

Bamboo has long been recognized as a renewable and abundant natural material, with excellent mechanical properties and rapid growth rates that make it a sustainable alternative to conventional timber and steel in construction [1]. Globally, its use is gaining attention as part of sustainable architecture and low-carbon structural systems [2]. However, despite these advantages, bamboo presents unique challenges: its culms are hollow, variable in geometry, and anisotropic in behavior, which complicates the design of reliable and standardized joints [3]. The lack of modular connection systems hinders broader application in engineered structures, especially in contexts where precision and safety are critical.

Recent advances in computational design and digital fabrication open possibilities to overcome these challenges by developing adaptive jointing systems [4]. Parametric modeling allows the integration of variability as part of the design logic rather than treating it as an obstacle. Through CAD/CAM workflows, geometric irregularities can be measured and translated into fabrication ready outputs, ensuring that bamboo's natural diversity is matched by a tailored joint system. This represents a significant step in aligning traditional construction materials with modern digital design practices [5].

The geometric variability of bamboo (diameter, ovality, taper, and wall thickness) prevents the direct application of conventional joint typologies. This results in poor fitness, structural inefficiency, or premature failure under loading [6]. In rural regions, where bamboo is often abundant, the absence of adaptable and standardized connection systems restricts its adoption in permanent or semi-permanent structures [7]. Furthermore, post-disaster reconstruction efforts often require materials and methods that are both cost-effective and rapidly deployable. The absence of scalable, adaptive fabrication solutions exacerbates these issues and limits bamboo's role as a mainstream construction material [8].

Without effective joint systems, bamboo structures remain vulnerable to localized failures at connection points, even when the material itself exhibits high tensile and compressive strength. This gap in technology not only undermines the reliability of bamboo as a construction resource but also perpetuates its perception as a "low-tech" or temporary material [9]. Addressing this problem requires a design methodology capable of absorbing geometric variability while simultaneously providing standardized outputs for fabrication, bridging the tension between tradition and modernity.

At the local scale, rural communities in Latin America and Asia rely heavily on bamboo for housing, infrastructure, and temporary shelters [10]. In these settings, structural failures linked to inadequate joints present safety risks and diminish community confidence in bamboo as a durable building material. At the global level, initiatives in sustainable architecture and the United Nations' Sustainable Development Goals (SDGs) emphasize renewable materials and resilient construction technologies [11]. Adaptive bamboo joint systems, particularly those informed by digital fabrication, represent an opportunity to connect global sustainability agendas with local construction practices.

Additionally, research on bamboo has highlighted its potential as a carbon sink and as a regenerative construction material, positioning it as a strategic resource in climate change mitigation [12]. By leveraging digital tools to enhance its usability, bamboo can become a viable component in both low-cost housing initiatives and advanced architectural

projects. Thus, the development of adaptive joint systems is not only relevant for rural resilience but also contributes to global innovation in sustainable design.
This study contributes to bridging the gap between computational design and low-cost construction. By developing a parametric CAD/CAM toolchain that generates adaptive steel joints, the research demonstrates how digital tools can encode structural rules and decision-support logic to account for bamboo variability [13]. The experimental validation confirms that simple parametric rules such as plate orientation can dramatically enhance performance, making bamboo safer and more viable as a structural material. Ultimately, this work positions digital fabrication as a catalyst for sustainable development, enabling rural communities to harness bamboo through efficient, scalable, and structurally sound construction systems.

The significance of this research lies in its dual contribution: advancing the field of digital design methodologies while addressing a pressing social and environmental challenge. By demonstrating that parametric workflows can deliver practical, low-cost solutions, this study validates the relevance of computational tools beyond high-tech laboratories and into real-world rural contexts. This positions the research at the intersection of technology, sustainability, and social impact an alignment that directly supports ICITS themes on software systems, modelling, and applied technologies.

The main objective of this research is to develop and validate a parametric CAD/CAM toolchain that generates adaptive steel joints capable of accommodating the natural variability of bamboo culms. Specifically, the study seeks to: (i) encode geometric and structural rules into a Grasshopper-based design workflow to ensure joints are automatically tailored to measured diameters, wall thicknesses, and connection angles; (ii) fabricate and assemble a steel prototype using accessible workshop tools to demonstrate the feasibility of translating digital models into manufacturable components; and (iii) experimentally evaluate the structural performance of the prototype through load–deflection testing, validating the contribution of decision-support rules such as plate orientation. By achieving these goals, the research aims to position digital fabrication as a practical solution to bridge the gap between computational design and sustainable rural construction practices.

The transition of bamboo from being perceived as a temporary "low-tech" resource to a mainstream engineered construction material depends heavily on the development of reliable, standardized connection systems. By integrating parametric workflows into rural construction, digital fabrication serves as a catalyst that allows local communities to harness bamboo through scalable and structurally sound methods. This approach ensures that the inherent natural diversity of the material—such as its varying diameter and wall thickness—is not viewed as an obstacle, but rather as a manageable parameter within a tailored joint system. Ultimately, shifting these computational tools from high-tech laboratories into real-world rural contexts validates their potential for significant social and environmental impact.

Furthermore, a critical component of this methodology is the encoding of structural heuristics and decision-support logic directly into the software environment. By automating the orientation of steel plates based on computed section properties, the toolchain significantly enhances the bending resistance of the joints by a factor of approximately 50x without requiring complex manual calculations from the end-user. Such adaptive systems are essential for bridging the gap between traditional building practices and modern digital precision, particularly in regions where rapid, resilient, and low-cost construction is a priority. This ensures that every joint is automatically tailored to the specific measured geometry of the culm, providing a level of safety and reliability that supports global sustainability agendas.

II. Methodology

A. Parametric modeling framework

The joint system was developed using Rhino 3D and the Grasshopper visual programming environment. The workflow accepts bamboo culm measurements as input and automatically generates fabrication-ready geometries for steel joints.

- Inputs (user-measured): outer/inner diameters, wall thickness, joint angle, and bamboo length.
- Parametric generation: Grasshopper scripts synthesize clamp rings and connector plates, scaling geometry to match culm variability.
- Rule-based logic: orientation of the plate's strong axis is enforced by computing the second moment of area, ensuring optimized bending resistance.
- Outputs: 2D cutting templates (DXF), 3D assembly models, and technical drawings for manual or CNC cutting.

Figure 1 shows parametric modelling of adaptive bamboo joints using Rhino and Grasshopper. The left panels show the generated 3D model of the joint, including clamp rings and plates adapted to bamboo diameter and geometry. The right panels present the Grasshopper visual programming definition, where user inputs (e.g., outer/inner diameter, wall thickness, joint angle) drive parametric constraints and rule-based logic. This workflow ensures fabrication-ready outputs (DXF templates and assembly drawings) tailored to variable bamboo culms.

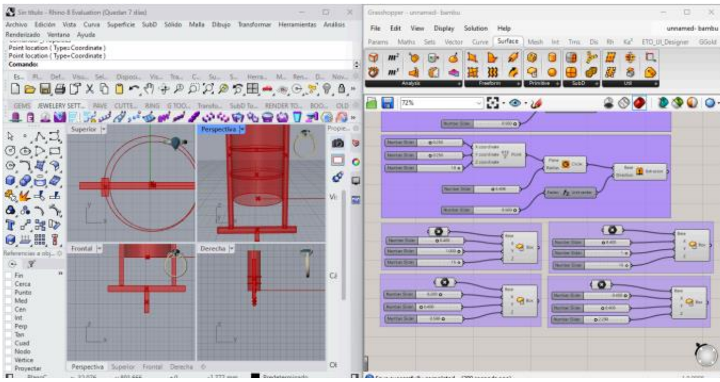

Fig. 1 Digital Workflow.

This system encodes geometric constraints, construction rules, and decision-support logic, enabling repeatable yet adaptive connections in rural contexts

B. Fabrication procedures

The digital output materialized into a steel prototype joint:

- Material selection: mild steel flat bars and rings (cut manually with saw and grinder).
- Assembly: welding of support plates and ring clamps, inserting of bolts for fastening.
- Surface treatment: painting to improve corrosion resistance.
- Bamboo preparation: selection of a 3-meter culm, diameter measured at multiple points to parameterize the model.

The fabricated joint was installed on the bamboo culm for load testing, final connector model rendered in SketchUp. The design integrates clamp rings and steel plates adapted to bamboo geometry, illustrating the joint's functional assembly in 3D. The perspective and orthogonal views highlight the distribution of plates, bolt positions, and ring clamps that ensure structural continuity. This representation bridges the parametric modelling stage with the fabrication phase, serving as a visualization of the adaptive joint before prototype manufacturing. see figure 2.

Fig. 2 Sketchup final modelling

C. Experimental procedure

To evaluate structural performance, a cantilever bending test was performed:

- Setup: a 3.0 m bamboo beam was fixed at one end with the parametric steel joint. The free end was subjected to incremental loading.
- Loading protocol: weights of 1–5 kg were applied progressively (≈9.8–49 N).
- Measurement: vertical deflection at the free end was recorded after each load increment.
- Termination: test continued until structural failure occurred at 49 N.

Fabrication and assembly of the adaptive joint prototype. The steel plates and clamp rings were cut, bent, and welded according to the parametric design, resulting in a manufacturable connector using accessible workshop tools. The top image shows the fitting of bamboo culms into the steel clamp during fabrication. The lower images present the completed steel connector and its integration with bamboo, highlighting bolt placement, clamp geometry, and welded reinforcements. This demonstrates the feasibility of translating parametric digital models into low-cost physical joints suitable for structural testing and rural construction applications, see figure 3.

Fig. 3 Real joints

D. Variables

TABLE I
VARIABLES

Independent Variables	Dependent Variables	Controlled Variables
Bamboo geometry (diameter, wall thickness, length).	Vertical deflection at free end (cm).	Bamboo species and condition (moisture content, age).
Joint angle (0–90°).	Failure load (N).	Joint material (mild steel, same thickness for all samples).
Load magnitude (1–5 kg increments).	Load–deflection linearity (stiffness).	Culm length (3 m for bending test).
Plate orientation (weak vs. strong axis).		Test configuration (cantilever with fixed clamp).

III. Results

A. Load – Detection behavior

The cantilever bending test produced a near-linear response up to 4 kg (39.2 N). Failure occurred at 5 kg (49 N), corresponding to bamboo splitting near the clamp rather than yielding of the steel joint.

Table 2 summarizes the applied loads, corresponding forces, and measured deflections.

TABLE II
LOAD–DEFLECTION DATA FROM CANTILEVER TEST

Load (kg)	Force (N)	Deflection (cm)	Observations
1	9.8	3.5	Elastic response
2	19.6	9.1	Elastic response
3	29.4	14.8	Elastic response
4	39.2	21.4	Elastic response
5	49.0	(failure)	Bamboo splitting

A linear regression through the first four points yields:

$$\delta=0.606P(R2\approx 0.998)$$

where:
δ = deflection (cm),
P = applied load (N).

This indicates a high correlation between applied load and displacement in the elastic range.

The effective stiffness (k) of the bamboo–joint system is:

$$k=\delta P\approx 1.65 N/cm (0.165 N/mm)$$

B. Section properties and plate orientation

To quantify the effect of plate orientation, the second moment of area (I) was calculated for two configurations of a rectangular steel plate (width b, height h):

$$Ix=\frac{bh^3}{12}, Iy=\frac{bh^3}{12}$$

Using the prototype dimensions:
Weak orientation: b=15 mm, h=3mm

$$\text{Iy} = \frac{3\,.\,(15)^3}{12} = 0.0338\ \text{cm}^4$$

Corresponding bending resistance ≈ 945 kgf/cm.

- Strong orientation: b=3mm,h=15mm

$$\text{Iy} = \frac{15\,.\,(3)^3}{12} = 84.375\ \text{cm}^4$$

Corresponding bending resistance ≈ 47,250 kgf/cm.

- The difference represents an improvement of nearly:

$$\frac{47{,}250}{945} = 50$$

Thus, orienting the plate along its strong axis increases resistance by ~50×, validating the design rule embedded in the parametric model.

C. Failure node

At 49 N, splitting initiated longitudinally along the bamboo culm near the clamp edges. The steel components remained intact, confirming that failure was governed by the bamboo substrate rather than the fabricated joint. This indicates that reinforcement strategies (e.g., clamping near nodes, use of sleeves or fillets) should be integrated in future iterations to mitigate stress concentration.

D. Summary of findings

- The bamboo–joint system exhibits a linear elastic response up to ~40 N, with stiffness k=0.165N/mm.
- Structural performance is highly sensitive to plate orientation, with a factor-of-50 difference in resistance.
- Failure mechanism was bamboo splitting, not joint yielding, suggesting improvements should target bamboo–joint interaction.
- The parametric CAD/CAM workflow successfully embedded structural rules (orientation) and produced fabrication-ready prototypes validated through experimental testing.

IV. Conclusion

This research demonstrated that the integration of parametric CAD/CAM workflows with rule-based logic provides an effective methodology for addressing the geometric variability inherent in bamboo culms. The developed toolchain, implemented in Rhino and Grasshopper, enabled the parameterization of culm geometry and the automated generation of fabrication-ready steel joints. Experimental results confirmed that the proposed system is technically feasible using accessible workshop processes, producing joints that sustained a linear elastic response up to 39.2 N before failure at 49 N, which was governed by bamboo splitting rather than yielding of the steel joint.

The analysis of section properties validated the effect of plate orientation as a critical design parameter. Calculation of the second moment of area demonstrated that orienting the connector plate along its strong axis increased theoretical bending resistance by a factor of approximately 50 times, which was consistent with the experimental performance trends. This validates the incorporation of structural heuristics into parametric rules, ensuring that the digital model embeds performance-driven design criteria.

Failure analysis indicated that the joint itself exhibited no yielding or plastic deformation under the tested conditions. Instead, longitudinal splitting of the bamboo culm near the clamp edges was the dominant failure mode, highlighting the need for reinforcement strategies to mitigate stress concentrations. Potential approaches include positioning clamps near nodes, incorporating compliant interlayers, and utilizing filleted clamp geometries to reduce shear-induced splitting. These measures should be systematically evaluated in future work under static, cyclic, and environmental loading conditions to define the operational limits of the system.

Beyond technical validation, the implementation of this adaptive toolchain addresses the socio-economic barriers that have historically relegated bamboo to temporary use. By automating the translation of irregular geometric data into precision-engineered steel connections, the system aligns local construction practices with the United Nations Sustainable Development Goals (SDGs) regarding resilient infrastructure and sustainable cities. This digital-to-analog bridge empowers rural communities to utilize bamboo not merely as a survivalist material, but as a strategic asset in global carbon sequestration efforts. The ability of the toolchain to produce reliable structures from locally abundant resources positions this methodology as a critical component in the transition toward a low-carbon built environment.

From a digital fabrication standpoint, the workflow demonstrated the ability to generate scalable and repeatable outputs, including DXF templates and assembly drawings, which are compatible with both manual and CNC-based manufacturing. This reinforces the reproducibility and adaptability of the approach across different fabrication environments. The contribution therefore lies in establishing a computational-to-physical pipeline that integrates geometric variability, codified structural rules, and accessible fabrication processes into a unified methodology for bamboo structures.

Furthermore, the decentralization of engineering intelligence via the Grasshopper environment provides a robust model for "knowledge-in-the-loop" manufacturing in resource-constrained contexts. By encoding structural heuristics directly into the design toolchain, the system ensures high-performance outcomes without requiring advanced structural expertise at the point of fabrication. The generation of fabrication-ready outputs ensures that the methodology is adaptable to a wide spectrum of technological environments, facilitating a transition from artisanal workshops to industrial scalability. Consequently, the research validates high-level digital design as a practical, low-cost solution for real-world architectural and social challenges.

In summary, the proposed parametric joint system constitutes a validated technical framework for the standardization of bamboo connections. Its capacity to reconcile natural irregularity with digital precision provides a foundation for future deployment in rural and low-cost construction. Further research should expand mechanical testing to encompass fatigue and durability studies, extend the parametric model to multi-joint assemblies, and optimize fabrication strategies for industrial scalability. These advances would consolidate bamboo's role as a renewable structural material and strengthen the scientific basis for its integration into sustainable construction systems.

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