Comparative Finite Element Analysis of 1D and 3D Bamboo Beam Models under Four-Point Bending

Nurwin Adam G. Muhammad
Department of Civil Engineering, College of Engineering and Technology, Mindanao State University - Iligan Institute of Technology

Jerson N. Orejudos
Department of Civil Engineering, College of Engineering and Technology, Mindanao State University - Iligan Institute of Technology

Mary Joanne C. Aniñon
Department of Civil Engineering, Gokongwei College of Engineering, De La Salle University

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Comparative Finite Element Analysis of 1D and 3D Bamboo Beam Models under Four-Point Bending

Nurwin Adam G. Muhammad[1,2], Jerson N. Orejudos[1], Mary Joanne C. Aniñon[3]
[1] Department of Civil Engineering, College of Engineering and Technology, Mindanao State University – Iligan Institute of Technology, Philippines.
[2] Department of Civil Engineering, College of Engineering, Western Mindanao State University, Philippines.
[3] Department of Civil Engineering, Gokongwei College of Engineering, De La Salle University.
Corresponding author email: nurwinadam.muhammad@g.msuiit.edu.ph

Abstract: *This study compares 1D and 3D finite element models in simulating the bending behavior of bamboo culms using ANSYS. Experimental data from four-point bending tests served as the benchmark for validating both models. The 1D model, based on beam theory, offers computational efficiency but simplifies stress distribution. In contrast, the 3D model captures more realistic geometric features and local stress concentrations. Results show that both models slightly overestimate experimental values, with the 3D model achieving closer agreement—predicting midspan moment and maximum load. Additionally, the 3D model more accurately captures tensile and compressive stresses at midspan. These findings highlight the trade-offs between computational simplicity and predictive accuracy and highlight the potential of 3D modeling for more reliable bamboo structural analysis.*

Keywords: Bamboo; bamboo structural analysis; finite element modeling

1. INTRODUCTION

Bamboo is a fast-growing, sustainable material known for its impressive strength, making it a promising alternative to industrial construction materials such as concrete and steel [1]. Its structural potential is particularly relevant in developing countries, where bamboo is abundant and rapid urbanization creates demand for cost-effective and renewable building materials. Beyond construction, bamboo also plays an essential role in the daily lives of millions in tropical regions, providing environmental, social, and economic benefits [2]. With widespread growth across Asia, America, and Africa, bamboo is readily accessible and well-positioned as a sustainable construction resource [3]. This aligns with global calls for sustainable development, such as the UN's 2030 Agenda and Sustainable Development Goals (SDGs), particularly SDG 11 on resilient and sustainable cities. Baskaran et al. [4] demonstrated the use of predictive machine learning models to assess SDG 11 performance, emphasizing the need for tools and materials that contribute to sustainable urban infrastructure. Similarly, the development of alternative construction materials has been explored by Sanni et al. [5], who assessed the mechanical properties of indigenous agro-waste for use in composite particleboards—highlighting the importance of local, renewable resources for sustainable building.

Despite bamboo's strong sustainability indicators and excellent mechanical properties, its use in structural engineering remains limited in many regions. Muhammad et al. [6] highlighted that this limitation stems from a lack of comprehensive research on bamboo's mechanical behavior and design principles. Their review identified key gaps in the current literature, such as limited guidelines for bamboo-specific load parameters, inadequate coverage of culm and connection behavior, and the need for species-specific standards. These findings underline the importance of advancing analytical and modeling tools to better understand and utilize bamboo in structural applications.

Finite Element Modeling (FEM) has emerged as a critical tool in structural analysis, enabling engineers to simulate and predict the behavior of materials and components under various loading conditions. FEM is particularly important for materials like bamboo, which exhibit orthotropic behavior, meaning their mechanical properties vary along different directions due to the natural alignment of fibers. Traditional modeling approaches often assume isotropy, which can lead to inaccurate predictions of stress and deformation in anisotropic materials like bamboo. As a result, FEM provides an effective framework for incorporating bamboo's directional mechanical properties and irregular geometry into structural analysis.

Extensive research has investigated the mechanical properties of bamboo [7–10] and developed tools for simulating bamboo connections in structural applications [11–13]. Aniñon and Garciano [14] reviewed various connection systems and emphasized the need for studies that account for species, age, treatment types, failure modes, and long-term performance. Meanwhile, Candelaria et al.[15] used ANSYS to model split bamboo beams with laminated layers to explore their composite behavior, while Ramful and Sakuma [16] studied the influence of geometry and material composition on bamboo's failure behavior under different loading conditions using nonlinear finite element modeling.

In this study, *Bambusa blumeana*, a native Philippine species with structural potential, is selected. Mechanical properties, including the flexural modulus of elasticity obtained from bending tests, are sourced from existing literature and used as input in numerical simulations. Two types of models are developed in ANSYS: a simplified 1D beam model and a more detailed 3D model. The 3D model follows ISO 22156:2021 guidelines, assuming linear isotropic behavior and using average cross-sectional dimensions. Both models replicate the experimental test setup, including node positioning, span length, and loading conditions.

The primary aim of this study is to compare the predictive performance of the 1D and 3D finite element models in simulating the bending behavior of bamboo culms. Specifically, the study evaluates the models in terms of loading, midspan moment, and tensile and compressive stresses at midspan. By comparing these outputs with experimental results, the study seeks to identify the trade-offs between modeling accuracy and computational efficiency.

2. Methodology

2.1 Experimental Data

Experimental data used in this study were obtained from literature [17] and follow the bending test procedures outlined in ISO 22156:2021[18]. The data served as the basis for defining the material properties and geometric parameters used in the numerical models. The study focuses on *Bambusa blumeana*, and the experimental setup involves a simply supported beam tested under static bending. Key geometric properties, including average diameter, wall thickness, and node thickness, were recorded, along with the modulus of elasticity parallel to the grain. Table 1 summarizes the material properties used as input in both the 1D and 3D finite element models.

Table 1. Data obtained from the experiment [17].

Material properties		
Average Diameter	85	mm
Average thickness	12	mm
Node thickness	5	mm
Modulus of elasticity parallel to fiber	20000	MPa

2.2 Numerical Analysis

This study employed two types of finite element models to simulate the bending behavior of bamboo beams: a simplified one-dimensional (1D) beam model and a more detailed three-dimensional (3D) solid model. Both models were developed using ANSYS software [19]12 and are used to evaluate flexural performance in terms of load-deflection response, midspan moment, and tensile and compressive stresses. The geometry and loading setup as shown in Fig. 1 and Fig. 2 follow the experimental configuration based on ISO 22156:2021 guidelines.

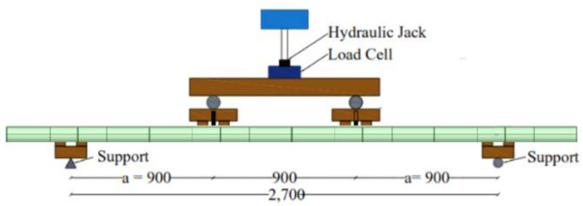

Fig. 1. Geometry modelling of bamboo beam.

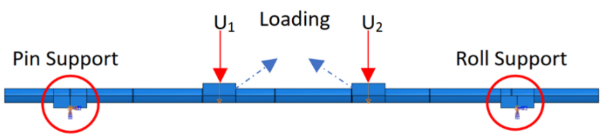

Fig. 2 Position of boundary conditions.

The 1D model was created using ANSYS Mechanical as a line element model with beam section definitions as shown in Fig. 3. The bamboo culm was idealized as a hollow circular cross-section, with average dimensions (diameter and wall thickness) taken from the experimental data summarized in Table 1. The modulus of elasticity was assumed to be 20,000 MPa, based on the experimental bending test.

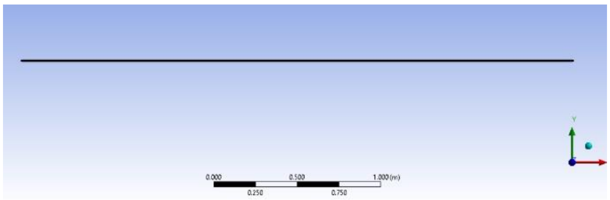

Fig. 3. 1D model constructed in ANSYS.

The cross-section was defined using ANSYS's beam section tool to capture the second moment of area and other relevant sectional properties. The node region was modeled with the same material and geometric properties but defined as a continuous part of the beam.
A fine mesh size of 10 mm was applied along the beam's length to ensure sufficient resolution for accurate deflection and moment results. The boundary conditions were modeled as simply supported with a pinned support at one end and a roller support at the other as shown in Fig. 2.
A displacement-controlled loading was applied at two loading points to replicate the four-point bending test. The loading span and support locations matched the experimental test. This 1D model offers a computationally efficient means of simulating the flexural behavior of the bamboo beam, albeit with simplified stress and strain distribution across the cross-section.
To capture a more detailed representation of bamboo's stress distribution, a full 3D solid model was also developed in ANSYS as shown in Fig. 4. The bamboo beam was modeled as a hollow prismatic cylinder with geometry replicating the physical test specimen. Parameters included average outer diameter, wall thickness, node placement, and total span length based on experimental observations.
The mesh was generated using 10 mm solid elements for the bamboo beam, while a coarser 20 mm mesh was used for the steel supports and loading plates to reduce computational demand while preserving accuracy in the bamboo component. The node region was integrated as a thicker cylindrical segment with bonded contact to the adjacent internode regions to ensure structural continuity.

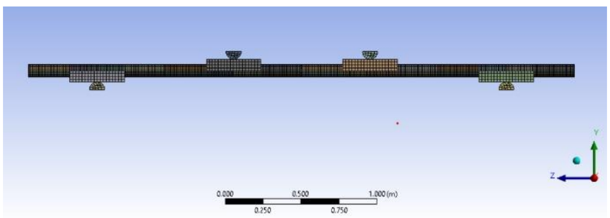

Fig. 4. 3D model constructed in ANSYS.

Contact interactions were defined between the bamboo outer surface and the loading fixtures. Frictional contact with coefficients of 0.1 (loading point), 0.3 (pin support), and 0.3 (roller support) were assigned. Bonded contacts were used internally at node-internode junctions.

Boundary conditions replicated the four-point bending test: the beam rested on a pinned support and a roller support, with vertical displacement imposed on the loading plates as per ISO 22156:2021. The 3D model provides a higher-fidelity simulation that allows for detailed stress visualization, including stress concentrations near nodes and contact regions, which are not captured in the 1D model.

After completing the simulations, key outputs were extracted from both the 1D and 3D finite element models to enable direct comparison with experimental data. Since the numerical models used displacement-controlled loading, the primary output was the reaction forces at the supports. These values represent the load induced on the beam as a response to the imposed midspan displacement. The total applied load, computed from the reaction forces, was then compared with experimental load measurements to assess the accuracy of the models.

The midspan bending moment was also determined from the support reactions, using the probe tool in ANSYS. This provided an accurate result of the internal moment at the section of maximum stress, which is critical for evaluating flexural performance.

In addition, the maximum tensile and compressive normal stresses at midspan were analyzed. In the 3D model, these were obtained directly from stress contours along the beam's length and cross-section, allowing for more detailed visualization of localized stress concentrations. In contrast, the moment from experimental result was using classical beam theory based on the calculated moment and the section modulus of the hollow circular section.

Finally, the deflection profile and overall deformation pattern were reviewed to verify that the maximum deflection occurred at midspan, consistent with the expected behavior of simply supported beams under four-point loading. These outputs, extracted at the peak imposed displacement of 48 mm, served as the basis for evaluating each model's performance and assessing the trade-off between modeling accuracy and computational efficiency.

3. Results and Discussion

3.1 Numerical Result and Analysis

The 3D numerical model uses material properties based on ISO 22156:2021, which assumes bamboo to behave as a linear isotropic material. Both 1D and 3D models were subjected to displacement-controlled loading, replicating a four-point bending test. The imposed displacement values correspond to experimental deflection data reported in the literature.

As shown in Table 2, the load induced on the bamboo beam at a deflection of 48 mm is 4,750 N based on experimental results. In comparison, the 1D model predicted a load of 5,094 N, and the 3D model predicted 4,883 N. Previous research conducted by Candelaria et al. [15], showed that the average error of the numerical analysis result using isotropic material assumption compared to the four-point bending test results of the bamboo split was 19.26%.

Both numerical models overestimate the experimental load, but the 3D model yields a prediction with a ratio between 3D and experimental of 1.0280 compared to the 1D model with ratio of 1.0724 as shown in Table 3. This indicates that the 3D model offers better accuracy in simulating the actual flexural behavior of the bamboo beam.

Table 2. Load induced on the beam at 48mm deflection.

Deflection (mm)	1D Model (N)	3D Model (N)	Experiment (N)
9.6	1018.8	976.6	950
19.2	2037.6	1953	1900
33.6	3565.8	3418.1	3325
48	5094	4883	4750

Table 3. Load comparison and ratio.

Deflection (mm)	1D / E	3D / E	1D/3D
9.6	1.0724	1.028	1.0432
19.2	1.0724	1.0279	1.0433
33.6	1.0724	1.028	1.0432
48	1.0724	1.028	1.0432

Similarly, Table 4 shows the computed midspan moment at the same displacement. The experimental moment was recorded as 2,300 N·m, while the 1D and 3D models predicted 2,693.5 N·m and 2,532.7 N·m, respectively. Again, the 3D model provides a closer approximation, with a ratio between 3D model to the experimental of 1.1010 compared to the ratio of 1.1710 in the 1D model as shown in Table 5.

Table 4. Moment at midspan at 48mm deflection.

Deflection (mm)	1D Model (N-m)	3D Model (N-m)	Experiment (N-m)
9.6	538.7	506.52	460
19.2	1077.4	1013.00	920
33.6	1885.45	1772.80	1610
48	2693.5	2532.70	2300

Table 5. Moment comparison and ratio.

Deflection (mm)	1D / E	3D / E	1D/3D
9.6	1.1711	1.1011	1.0635
19.2	1.1711	1.1010	1.0636
33.6	1.1711	1.1011	1.0635
48	1.1711	1.1011	1.0635

This trend of overprediction is observed across the entire displacement range, with the 1D model consistently producing higher moment values than both the 3D model and the experimental results. This can be attributed to the geometric simplifications inherent in the 1D model, which assumes a uniform beam cross-section and does not fully capture variations in geometry or stiffness along the culm. In contrast, the 3D model incorporates detailed geometry, including wall thickness and node positioning, which contributes to a more accurate representation of moment distribution under bending. As a result, the 3D model achieves closer alignment with experimental observations, particularly at higher displacement levels where geometric nonlinearity and stress concentration effects become more significant.

The numerical models, both 1D and 3D, were subjected to displacement-controlled loading consistent with the four-point bending experimental setup. The displacement applied at midspan was based on the values recorded from literature experiments.

A displacement-controlled loading of 48 mm was applied to both numerical models to evaluate flexural behavior, with the resulting load and midspan moment values summarized in Tables 2 and 3. The 3D model showed closer agreement with experimental values compared to the simplified 1D model, highlighting the improved accuracy gained from incorporating greater geometric and material complexity. The deformation and stress distribution patterns under four-point bending are illustrated in Fig. 5 and Fig. 6. The 1D beam model as illustrated in Fig. 5 presents a smooth, generalized distribution of tensile and compressive stresses along the beam's length, consistent with classical beam theory. However, this approach lacks the resolution to depict localized effects such as stress concentrations near supports and loading points or irregularities in the bamboo's internal structure.

In contrast, the 3D model as presented in Fig. 6 provides a more detailed visualization of stress distribution, particularly around nodes and load application areas. It captures how stress varies not only along the beam's length but also across the cross-section, revealing zones of stress intensification that may lead to failure. These visualizations underscore the trade-off between computational cost and model fidelity: while the 1D model is more computationally efficient and suitable for quick assessments, it cannot replicate the localized stress behavior evident in the 3D simulation. The 3D model, although more resource-intensive, more accurately reflects the mechanical response of real bamboo culms, which are inherently anisotropic and heterogeneous in structure.

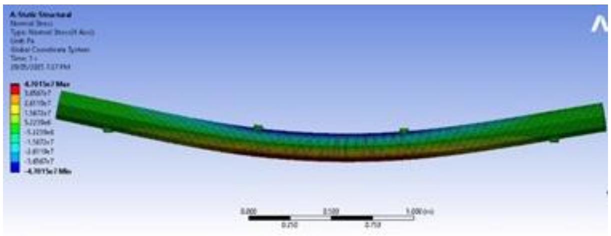

Fig. 5 Stress Distribution from 1D Beam Model under Four-Point Bending.

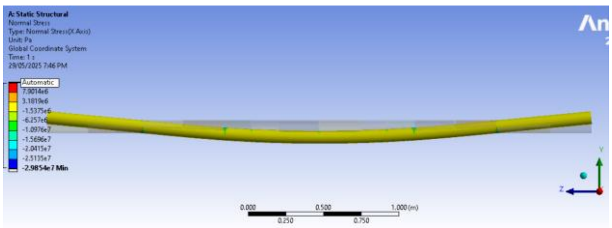

Fig. 6 Stress Distribution from 3D Beam Model Showing Stress Concentrations.

While Fig. 6 broadly depicts stress concentrations along the beam, Fig. 7 specifically focuses on stress distribution at the midspan, where maximum bending moment occurs. This figure reveals a non-uniform stress profile across the cross-section of the culm, highlighting regions of elevated tensile and compressive stresses. These localized intensifications align with expected patterns for flexural behavior but are only captured in detail through a 3D representation. This level of stress resolution is not possible in the 1D model and underscores the importance of spatial stress mapping in structural safety assessment.

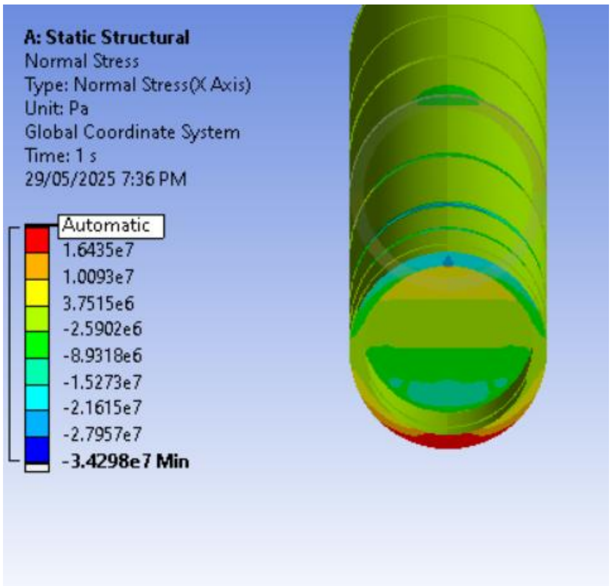

Fig. 7 Stress Distribution at midspan from 3D Beam Model.

Fig. 8 and Fig. 9 show the deformation patterns from the 1D and 3D models, respectively, under four-point bending. Both models exhibit visually similar deflected shapes, characterized by a smooth, symmetric curvature typical of flexural deformation. This consistency is expected, as identical boundary conditions and vertically applied displacement loads were used in both simulations. The similarity in deformation confirms that both models are correctly replicating the global structural response to the imposed loading. However, while the overall shape is similar, the 3D model still offers additional insight, particularly in capturing the distribution of internal stresses and potential stress concentrations near loading and support points, as seen in Fig. 6 and Fig. 7.

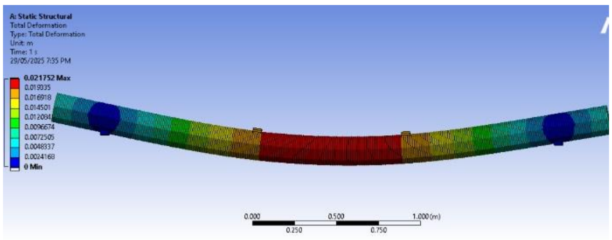

Fig. 8 Deformation pattern from 1D Beam Model.

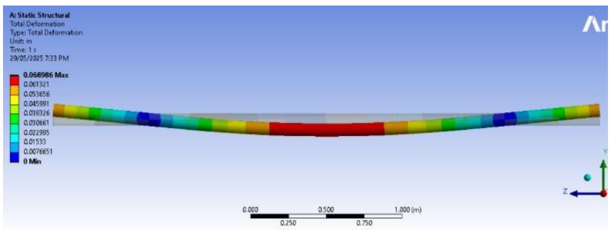

Fig. 9 Deformation pattern from 3D Beam Model.

Both numerical models in this study assume isotropic material behavior, as defined by ISO 22156:2021. While this assumption simplifies simulation and aligns with standard practice, it overlooks the anisotropic and layered fiber structure of bamboo, which significantly influences stress transfer and deformation. Incorporating orthotropic material models, which define direction-specific properties, could yield more realistic results and further improve prediction accuracy.

Muhammad et al. [6] highlight this gap in current modeling practices, emphasizing the limited design philosophy for bamboo structures due to insufficient understanding of material behavior, especially concerning fiber orientation, load-specific parameters, and connection behavior. Their findings reinforce the need for enhanced guidelines and modeling standards that account for species-specific characteristics and local anisotropy.

The current results also resonate with those of Ramful and Sakuma [16] who demonstrated the critical role of geometry and fiber distribution in predicting bamboo failure under complex loading. Similarly, Candelaria et al. [15] modeled laminated split bamboo beams and noted the importance of capturing composite action and stress variability. These studies collectively support the direction of this work and suggest that future research should move toward orthotropic and nonlinear modeling to fully leverage bamboo's structural potential in engineered applications.

4. CONCLUSION

This study compared one-dimensional (1D) and three-dimensional (3D) finite element models in predicting the flexural behavior of bamboo culms based on four-point bending experimental data. The 1D model provided a computationally efficient and simplified approach, while the 3D model offered a more realistic representation of the bamboo's geometry and stress distribution under loading.

Results indicated that both models slightly overestimated experimental values; however, the 3D model consistently produced load and midspan moment predictions that were closer to the experimental results. Furthermore, only the 3D model successfully captured stress concentrations around supports and loading points—critical features that the 1D model, due to its geometric simplifications, was unable to represent.

Overall, the 1D model remains useful for quick, preliminary assessments, especially when computational resources are limited. However, the 3D model demonstrates superior accuracy and provides more meaningful insights into localized stress behavior, making it more suitable for detailed structural evaluation. The choice between the two modeling approaches should be guided by the specific objectives of the analysis and the required level of detail.

Future work should consider incorporating orthotropic material properties to better reflect bamboo's anisotropic nature, which could further improve the predictive accuracy and applicability of numerical models in bamboo structural design.

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