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Bamboo (Dendrocalamus Asper) as an Eco-Friendly Sustainable Material: Optimising Mechanical Properties and Enhancing Load-Bearing Capacity for Environmental Architectural Design

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ABSTRACT

This study will assess the utilisation of Bamboo (a Thai vernacular material) in the construction industry. Bamboo is a sustainable and environmentally friendly material which provides a suitable alternative to traditional construction materials. This research will examine its mechanical strength properties as determined by a review of the existing literature and an examination of the bearing area variations of bamboo nodes.

The research data and ensuing experiments facilitated the simulation of the load-bearing capacities of bamboo columnar and beam structures via optimisation. Additionally, this study examined the limitations of bamboo-based structures. The assimilation of mechanical property data and bamboo strength was imperative for the production of load-bearing simulations for bamboo columns and beams within ANSYS software. In many countries, bamboo is a commonly employed construction material because of the many benefits it provides such as its rapid growth speed. The compressive strength tests conducted in this study revealed that the middle nodes could withstand up to 64.9 kN, which was the highest value amongs the three samples tested. These findings will contribute to ongoing optimisation and research regarding the damage mechanisms affecting column and beam structures under load. Notably, this damage was prevalent at the junctures of column and beam interfaces. The intention is to conduct additional research that will enhance the current understanding and ensure the sustainability of bamboo as an architectural building material.

Keywords: sustainable construction material, material performance, construction and building material, low-carbon material for architecture, environmentally friendly

INTRODUCTION

Sustainability is based on three key pillars: environmental, social, and economic. According to the environmental aspects outlined on the website of the environmental, these recommendations can enhance environmental quality (Wurianturi et al., 2022).

Bamboo is a material that has acquired significant interest in Thailand due to it being a natural resource that is widely available and easily grown. In addition to its physical properties, which make it suitable for use in construction, bamboo is an environmentally friendly material that can significantly reduce carbon emissions. The mechanical properties of bamboo include its significant strength and tolerance, which make it an advantageous building material. Its bending strength aligns with wood classification criteria, suggesting its appropriateness for structural applications such as building columns, beams, and scaffolding. Additionally, its rapid growth characteristics contribute to its environmental benefits by making it a sustainable and efficient alternative for the construction industry; the robust exterior of bamboo is comparable to reinforced concrete, which enables it to withstand considerable amounts of compression and tension.

Bamboo and the Lifestyle of the Thai Community

Thailand is a country which contains a multitude of foliage, particularly bamboo, which provides several economic and social benefits. Bamboo occurs in many different varieties and is known as a pioneer species owing to its rapid growth rate in a variety of environments such as fertile forests or deteriorating forestry regions. Bamboo can be found in almost all regions of Thailand (including the Northern, Central, Western, Eastern, Northeastern, and Southern regions) and tropical zones across Asia.

In Thailand, several species of bamboo including Dendrocalamus asper and Dendrocalamus strictus have been evaluated for their physical and mechanical properties. These species have demonstrated efficiencies comparable to hardwood and are capable of bearing high compression and tension exceeding 600 kg/cm² and 900 kg/cm², respectively. Such attributes are critical for structural applications including building support, bridges, and any construction requiring durability against compressive and tensile forces (as shown in Figure 1). The use of bamboo provides multiple benefits for construction: it is well-suited for sustainable building, particularly in lightweight structures that require long spans for increased space while maintaining load-bearing efficiency. The use of bamboo as a building material provides many advantages:

- **Tolerance to Varying Climates**

Bamboo exhibits an effective tolerance to fluctuating weather conditions, which makes it suitable for use in regions with high levels of humidity and elevated temperature.

- **Rapid Growth and Distinctive Qualities**

As a rapidly growing species with exceptional qualities, bamboo is preferred in construction and building projects that demand high-quality, precision materials.

- **Reduced Need for Chemical Treatment**

The inherent resistance of bamboo to insects and diseases minimises the need for chemical treatments such as pesticides and insecticides in building applications.

- **Sustainability (SDGs)**

The adoption of bamboo in construction minimises the reliance on unsustainable materials such as treated wood and metals which are environmentally detrimental.

- **Economic Benefits**

The utilisation of bamboo stimulates local economies by creating market opportunities for communities to trade bamboo and its related products thereby generating income and promoting economic growth at a regional level.

Research Question

How can a study regarding the properties of bamboo contribute to the attainment of sustainability in environmentally friendly design, and how robust is it as a key structural component of buildings?

Figure 1

Thai Vernacular Material, Bamboo for Construction

Note. From *making high-quality building materials with bamboo*, by D. I. Manila, n.d., Base-builds (https://base-builds.com/2023/05/19/from-harvesting-to-building-making-high-quality-building-materials-with-bamboo/). Copyright by Base-builds.

MATERIALS AND METHOD

Bamboo is an overarching term used to describe the plants of the Gramineae or Poaceae family, which are characterised by their unique structure. Their stalks exhibit pronounced internodes and bear grass-like leaves.

Bamboo plants are propagated via vegetative reproduction and are well-recognised for their rapid growth; they can grow to their maximum size in a relatively short period. Typically, bamboo stalks are robust, tall, and capable of thriving in both warm and cool climates. In many Asian and Pacific regions, bamboo has many uses and is frequently employed as a construction material for creating roof tiles or ornamental items for internal decoration (Chan-aek, 2021). Beyond these applications, bamboo is a fundamental component of many industries, notably in the construction of diverse structures which require a range of different-sized materials. For example, the diameter of bamboo stalks ranges from 0.7 to 7 inches and they can grow between 1 and 60 feet tall.

Thailand is replete with forestry consisting primarily of bamboo which provides the country with numerous social and economic advantages. Contemporary research has identified Thailand as the foremost focal point for bamboo cultivation and it contains 82 species across 15 families. Bamboo construction is a fundamental feature of Thai culture and dates back to ancient times when it was utilised as a construction material and for the creation of household furniture such as chairs, tables, shelves, and wardrobes (as shown in Figure 2).

The optimal species of bamboo for structural and construction applications are those with straight, sturdy, and durable stalks such as Dendrocalamus and Gigantochloa which are renowned for their mechanical strength and adaptability, which makes them perfect for use in a variety of architectural and industrial contexts. Moreover, the straightness of their stalks prevents warping during processing while their robust nature allows them to bear significant loads, making them suitable for use in scaffolding and sizeable structural frameworks in sustainable construction. Bamboo's ecological adaptability is one of its most valuable traits; it can thrive in a wide range of climates, from cold, high-altitude mountainous regions to the warm, humid tropical zones found across East Asia. This adaptability extends not only to temperature ranges but also to variations in soil types and moisture levels which enable bamboo to colonise diverse ecosystems. Its ability to develop rapidly and regenerate after harvesting further enhances its ecological versatility and makes it a highly renewable resource. Bamboo forests are primarily located in Asia; therefore, the plant has become a critical regional resource. Countries such as China, India, Thailand, and Indonesia are home to vast reserves of bamboo, and it is a critical component of the daily lives of many communities. Historically, the abundance of bamboo in these regions has supported the region's economic and cultural development. It is employed extensively in traditional craftsmanship as a construction material and as scaffolding, and in modern industrial contexts it is used in textile manufacturing, paper production, and furniture production. Furthermore, its availability and versatility make bamboo an indispensable natural material for countless industries; simultaneously, it provides crucial support to local economies and provides a livelihood for millions of people.

In these countries, bamboo is deeply embedded in the cultural fabric of society. For centuries, bamboo has been utilised in the construction of homes, agricultural tools, household items, and musical instruments. Its widespread use in traditional building practices continues today, where it remains an integral part of vernacular architecture, particularly in rural areas. However, the use of bamboo has expanded into modern building practices, where its ecological benefits and structural strength are increasingly recognised in sustainable construction projects. Modern innovations, such as engineered bamboo products, allow it to be used in more advanced architectural designs and contribute to environmentally friendly construction efforts.

Furthermore, bamboo's resilience and ecological adaptability make it an ideal material for addressing global environmental challenges. Bamboo grows rapidly, with some species maturing in as little as three to five years, making it one of the fastest-growing renewable resources. Its ability to regenerate quickly without the need for replanting minimises deforestation pressures on other natural resources. Additionally, bamboo is a fundamental contributor to carbon sequestration because it absorbs significant amounts of carbon dioxide during its growth, which mitigates the effects of climate change by reducing the quantity of greenhouse gases in the atmosphere. Bamboo's extensive root systems provide enhanced stability to the surrounding soil, prevent erosion, and improve water retention, making it a valuable tool for the restoration of the ecosystem in degraded areas. The prevalence of bamboo in Asia accounts for the region's longstanding relationship with the plant: it serves as a material for everyday use and is celebrated as a symbol of resilience, flexibility, and adaptability. The cultural importance of bamboo is celebrated in art, literature, and festivals, which celebrate it as a symbol of strength, endurance, and tenacity.

In addition to its practical applications, bamboo holds a spiritual and philosophical significance in many Asian cultures where it represents harmony between humans and nature. Bamboo's unique combination of ecological benefits and cultural importance positions it as a cornerstone of sustainable development in the 21st century. As global attention shifts towards addressing environmental challenges such as deforestation, loss of biodiversity, and climate change, bamboo offers a viable solution for sustainable growth. Its renewable nature, combined with its wide-ranging applicability, makes bamboo a critical resource for promoting sustainable practices that benefit the regional and global environment as well as local communities. By integrating bamboo into global sustainability efforts, countries can contribute to a greener economy while preserving cultural heritage and protecting natural ecosystems. In conclusion, bamboo's economic, cultural, and environmental significance in Asia emphasises its potential as a critical resource for addressing global sustainability challenges. Its versatility and resilience, combined with its entrenched cultural heritage, make bamboo an ideal material for future sustainable development initiatives throughout Asia and around the world.

When selecting the most appropriate species for use in construction, it is widely acknowledged that the preferred varieties are those with straight, broad, and durable stalks such as Dendrocalamus and Gigantochloa.

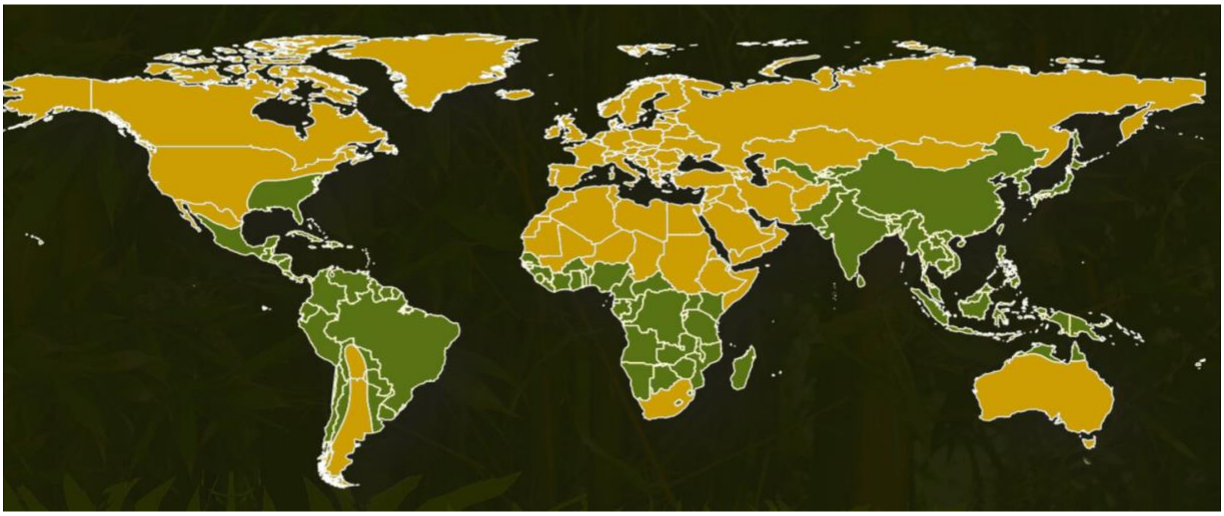
Figure 2

Bamboo weaving pattern

Note. From *Adhere to the principles of sufficiency economy: Selling basketry to create a living and make ends meet*, by S. Thipudorn, 2016, (https://www.naewna.com/local/243439). Copyright by Naewna.

Figure 3

Distribution of Native Bamboos around the world



Note. From *Bamboos: Where does bamboo grow*, by S. Schröder, 2024, (https://www.guaduabamboo.com/blog/where-does

As shown in Figure 3, Sharma et al. (2014) note that each species of bamboo is distinguished by one of three root systems: sympodial, monopodial, or amphodial. The thickness of bamboo decreases along the height of the culm while the fibre density increases from the culm's inner wall to its outer wall. A case study concerning a school building in Ghana highlights bamboo as a locally sourced, undemanding structural material. Additionally, research has been conducted in Ghana to evaluate the cost-effectiveness and structural integrity of bamboo as a building resource. Consequently, numerous countries continue to utilise bamboo in both traditional and modern construction projects. Its adaptability, strength, and eco-friendliness have made it a desirable material for the creation of a sustainable infrastructure.

Bamboo's ecological adaptability allows it to flourish in a variety of climates, from the cold, mountainous regions to the warm, tropical zones which encompass East Asia. Approximately 65% of bamboo forests are located in Asia (Paridah, 2013), particularly in regions with abundant bamboo forests. Countries in Africa, Asia, and Latin America have recognised the benefits of bamboo as a renewable resource and a material that promotes local economic development.

Moreover, bamboo has proven to be a robust and economically viable option (Solomon-Ayeh, 2005). Historically, it has served as a global construction material for centuries and the traditional methods of bamboo production have experienced widespread application, especially in Latin America (Archila-Santos et al., 2012). In structural engineering, bamboo is frequently utilised within the wall systems of one- and two-storey structures (Mena et al., 2012).

Studies concerning the employment of bamboo in construction reveal that the prevalent structural form consists of load-bearing bamboo walls overlaid with cement to provide protection against the climate and to reinforce structural integrity (Escamilla et al., 2014). However, not all species of bamboo are suitable for construction. The genera of bamboo that are acknowledged for their quality and suitability for construction include Dendrocalamus, Gigantochloa, Thyrsostachys, Bambusa, and Schizostachyum (Chaowana et al., 2021). However, several limitations exist when utilising bamboo as a building mat, particularly in urban environments where building regulations may be more stringenterial, such as the substantial labour required to utilise bamboo effectively. Moreover, specialised infrastructure and expertise are often necessary to utilise bamboo effectively.

In many cases, traditional bamboo construction skills are being lost or replaced by more modern building techniques, making it essential to invest in training and capacity-building for bamboo-based projects (as shown in Figure 4 and 5). Another limitation of bamboo concerns its susceptibility to moisture and insects. If it remains untreated, its durability will be compromised and it will require additional treatments and repair, which will result in increased labour and maintenance expenditure. However, with proper treatment and the correct construction techniques, bamboo is a highly sustainable and cost-effective alternative to traditional materials, especially in regions where it grows abundantly.

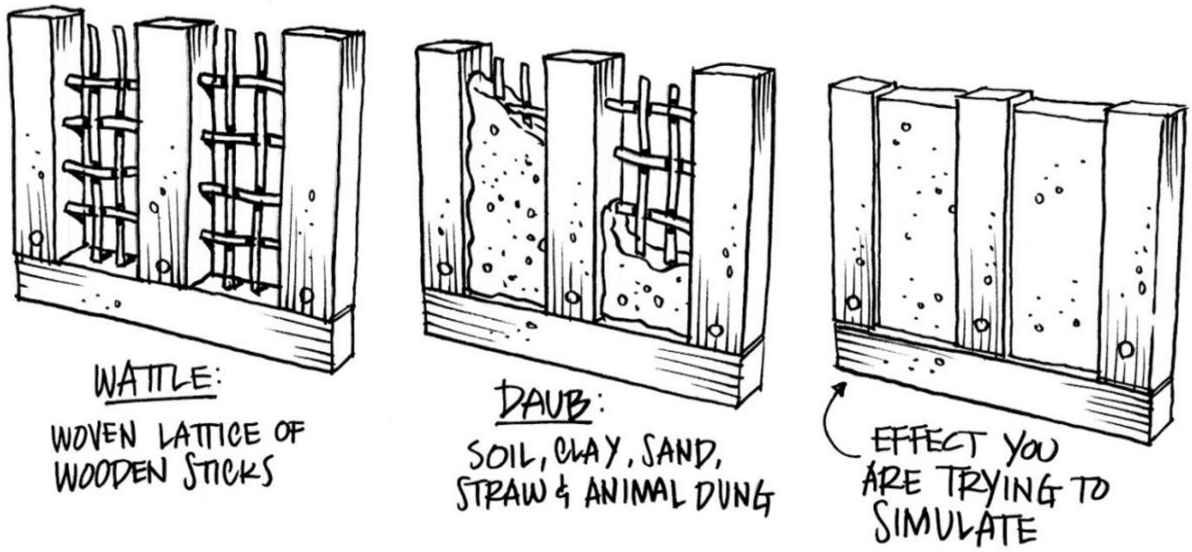
Another consideration that requires addressing when using bamboo concerns quality control issues arising from the natural variability of bamboo (Chaowana et al., 2021). Despite these issues, bamboo remains a cost-effective option for residential construction and is particularly useful in post-disaster reconstruction (Manandhar et al., 2019). The optimal maturity of bamboo for building purposes is between three and four years; specimens younger than three years or older than five years are deemed unsuitable (Awoyera & Adesina, 2017).

In Thailand, bamboo forms an integral part of structural works and several studies including one conducted by Phakhiri (1997), have examined the physical and mechanical characteristics of species such as Dendrocalamus. Comparative research conducted by Sangsuwandee (2019) involving pine, bamboo, and steel has revealed that bamboo possesses superior tensile and bending strength than pine and, in some instances, steel (see Table 1,2 and 3). Furthermore, the tensile strength-to-weight ratio of lightweight bamboo was found to be six times that of steel.

The physical and mechanical properties of bamboo from various species are often the subject of studies with specific aims, such as engineering research that primarily focuses on the application of bamboo in structural works or agricultural research concerning soil enhancement and the augmentation of agricultural yield. Such investigations are essential to recognise and quantify the distinct properties of each bamboo species such as strength, weather resistance, erosion, and tolerance to sunlight and humidity.

Figure 4

Bamboo Woven Lattice, Earth Building



Note. From *Techniques for building a mud house: Weaving and filling soil*, by OoyWhan, 2015, (https://www.bansuanporpeang.com/node/29180). Copyright by Bansuan Porpeang.

Figure 5

Bamboo Woven Lattice, Earth Building

Table 1

Compared Bearing Capacity Among Pine, Bamboo, and Steel

Name	Pine	Bamboo	Steel (St37)
Elastic Modulus	1,100	2,000	2,000
Compressive Strength	4.3	6.2 –9.30	14
Tensile Strength	8.9	14.8 – 38.4	16
Bending Strength	6.8	7.6 –27.6	14
Shearing Strength	0.7	2	9.2

Table 2

Mechanical Properties of Dendrocalamus

Position	Results		
	Fresh Density (g./cm^3)	Dry Density (g./cm^3)	Moisture (%)
Base	0.701	0.586	25.971
Middle	0.696	0.628	11.032
Tip	0.772	0.669	8.018

Note. From *Mechanical properties of Thai structural bamboo for simple structure*, by S. Banjongrat, 2014, Thammasat University. Copyright 2014 by Thammasat University.

Table 3

Mechanical Properties of Dendrocalamus

Position	Results			
	Compressive strength parallel to grain (kg./cm^2)	Compressive strength perpendicular to grain (kg./cm^2)	Shearing strength (kg./cm^2)	Tensile strength (kg./cm^2)
Base	404.12	74.29	97.96	2,493.99
Middle	563.36	83.61	120.65	1,473.66
Tip	730.59	112.07	136.47	-

Note. From *Mechanical properties of Thai structural bamboo for simple structure*, by S. Banjongrat, 2014, Thammasat University. Copyright 2014 by Thammasat University.

Connecting individual bamboo stems to form a coherent structure is challenging due to its hollow composition and uneven texture. Achieving adherence and robust connections in such structures necessitates the application of appropriate techniques and materials to ensure optimal outcomes and long-term durability (see Figure 6) (Institute for Lightweight Structures, 1985).

Modern construction employs contemporary connection materials, such as threaded rods with nuts and washers at both ends, to bind the bamboo poles and enhance the strength and aesthetic appeal of the assembly. The use of steel bolts facilitates the creation of robust, complex connections which are not feasible when using binding. Additionally, concrete is poured inside the bamboo internode for joints that will experience elevated shear stress (Vahanvati, 2015).

Historically, the bamboo elements of a construction were combined via the use of ropes. Traditional lashing techniques have created connections of two to four culms via the utilisation of full or end-notched culms and the absence of puncturing or adhesives (see Figure 7) (International Organization for Standardization, 2018).

Simple connections relied solely on the tensile capacity of the lashing material to take the joint load while more complicated connections occasionally featured additional compression members as cross-bracing.

Bolts allow for increased precision and can bear more significant loads than lashing which enhances the overall stability of the structure. This increased strength is particularly important in projects that require long-term durability, such as bridges, large shelters, or multi-storey bamboo buildings. Additionally, bolts can be tightened and adjusted as needed, ensuring that the structural connections remain secure over time. While bolting is a time-efficient and more robust construction solution, it is important to acknowledge environmental factors.

The introduction of steel bolts has reduced the sustainability of bamboo structures. The steel must be manufactured and transported, which increases the carbon footprint of the project; however, these shortcomings are often negated by the increased lifespan and structural integrity that bolting provides, particularly in urban or modern construction contexts where long-term stability is crucial.

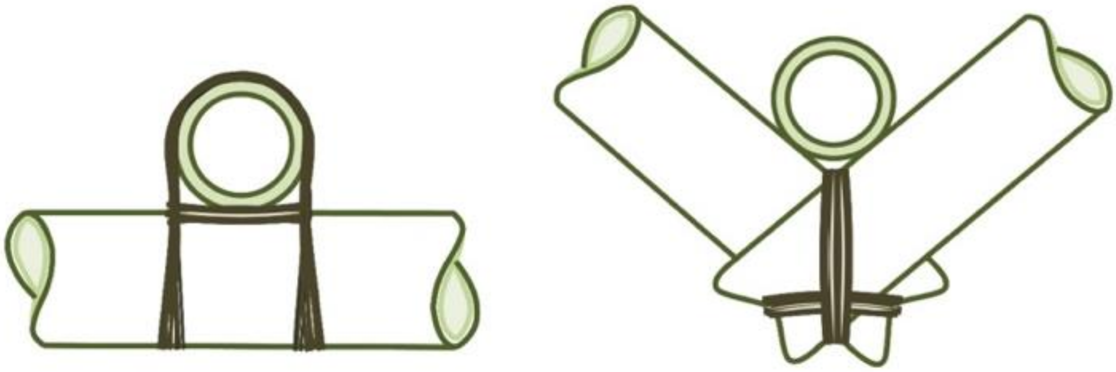
Figure 6

Samples of the Joint Structure From a Bamboo Building

Note. From *Son La Restaurant / VTN Architects*, 2014 (https://www.archdaily.com/559125/son-la-restaurant-vo-trong-nghia-architects?ad_medium=gallery); from *Community Center Camburi*, by P. Vada, 2018 (https://www.archdaily.com/906024/community-center-camburi-cru-architects?ad_medium=gallery); and from *Tea House / Pablo Luna Studio*, by H. Abdel, 2020 (https://www.archdaily.com/984070/tea-house-pablo-luna-studio?ad_medium=gallery). Copyright 2014, 2018, and 2020 by ArchDaily.

Figure 7

Connected Bamboos in the Past



Note. From *Son La Restaurant / VTN Architects*, 2014 (https://www.archdaily.com/559125/son-la-restaurant-vo-trong-nghia-architects?ad_medium=gallery). Copyright 2014 by ArchDaily.

In conclusion, the utilisation of steel bolts in bamboo construction represents a significant advancement by making the fabrication process increasingly efficient, reliable, and durable. It should be noted that this process requires a sound understanding of engineering principles and how to effectively integrate triangulation within a design. With the appropriate expertise and techniques, bolting can enhance both the efficiency and structural performance of bamboo-based buildings.

The current research elected to analyse mature Dendrocalamus bamboo. This process involved chemically treating the specimens in a boric and borax solution for seven and ten days (as shown in Figure 8 and 9), respectively. Following this, the specimens were naturally dried to eliminate moisture (Forest Research Office, n.d.). This treatment method is critical for the removal of starch from the bamboo sample (as shown in Figure 10).

Additionally, this process is a preventive measure designed to minimise weevil infestation and is a standard procedure for bamboo that is intended for construction or structural applications.

Subsequently, the characteristics of the bamboo were categorised into three distinct types based on their nodal positions: top nodes, middle nodes, and bottom nodes. Identification codes were assigned to track the sequence and number of bamboo samples tested (as shown in Figure 11 and 12).

Figure 8

Bamboo Treatment Using Boric and Borax

Figure 9

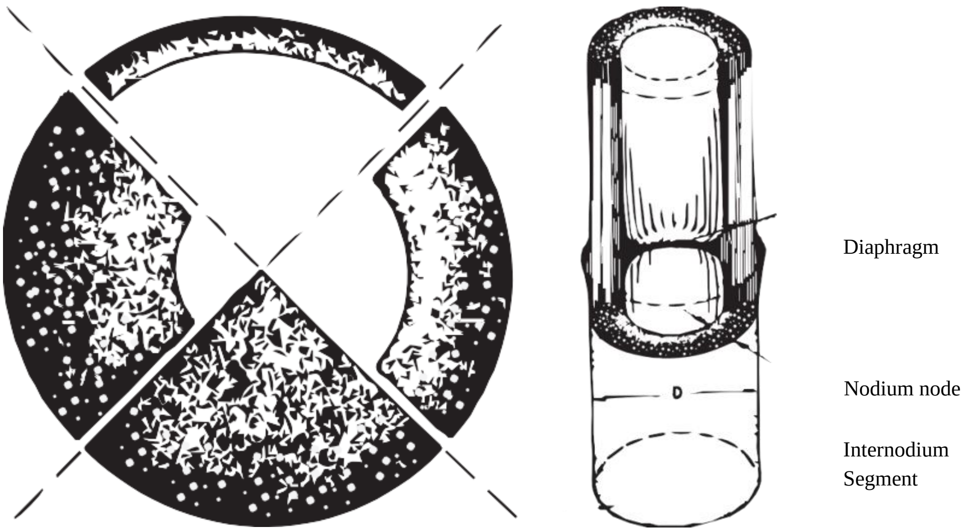
Bamboo Treatment Using Boric and Borax

Figure 10

Dendrocalamus Asper

Figure 11

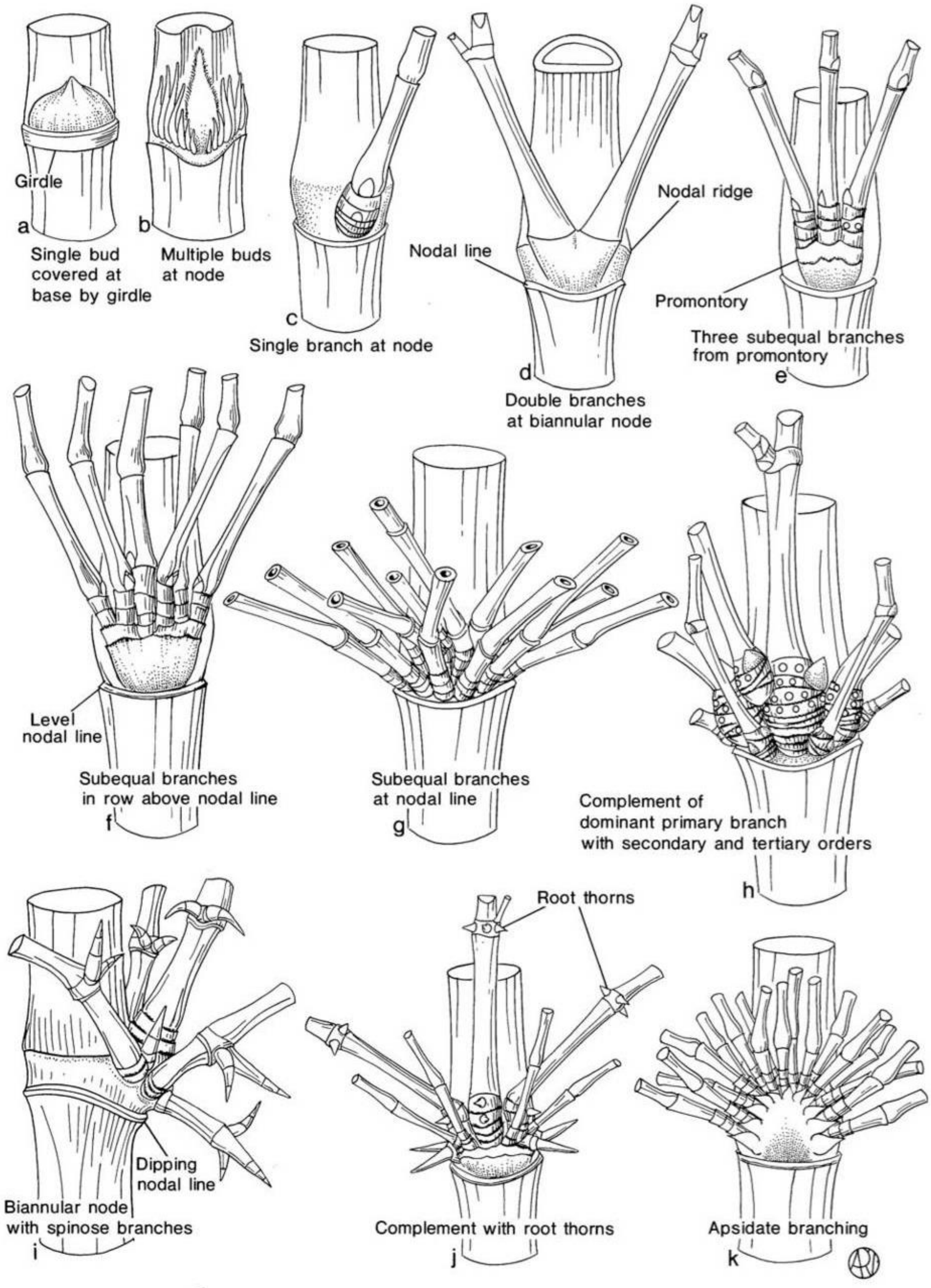
Nodes



Note. From *Identifying bamboos in the vegetative stage*, by M. L. Sharma and N. Chongtham, 2020, Panjab University. Copyright 2018 by Panjab University.

Figure 12

Nodes



Note. From *Identifying bamboos in the vegetative stage*, by M. L. Sharma and N. Chongtham, 2020, Panjab University. Copyright 2018 by Panjab University.

Bamboo serves essential ecological functions in the environments where it propagates. It provides a habitat and a food source for a range of animals including the endangered giant panda, red pandas, and other herbivores that rely on bamboo for survival. Additionally, bamboo plays a fundamental role in stabilising soil, preventing erosion, and promoting biodiversity. Its rapid growth allows it to quickly reforest areas that have been cleared, which facilitates the restoration of deteriorating ecosystems.

The bamboo samples analysed in this study were 30 centimetres in length and had a diameter of 2.5 inches. The study found that there was a direct correlation between the thickness of the bamboo and its outer diameter. Janssen (2005) noted that bamboo with increased wall thickness possessed enhanced resistance to external forces. To organise and record the data efficiently, the researcher assigned codes to the samples (see Table 4).

Following treatment with boric and borax, the structural characteristics of the bamboo fibres became more crystalline.

The overall compressive strength of Dendrocalamus Asper which had undergone optimisation was evaluated at several nodal locations.

Bamboo is acknowledged as a rapidly growing plant material that offers structural strength efficiency. The study's objectives included performing a comparative analysis of joint capacities and an evaluation regarding the potential of bamboo for use in building structures. This research intends to advance the use of bamboo as a construction material and its effectiveness in structural design (as shown in Figure 13).

Any surface modifications of the bamboo fibre following treatment were ascertained by a scanning electron microscope (SEM) (as shown in Figure 14).(Júnior et al., 2014).

Research evaluated the force and load-bearing capacities of bamboo via an ANSYS simulation (as shown in Figure 15).

The optimisation process is designed to measure the elastic strength (including maximum elastic strength, elasticity upon breakage, and modulus) of the stable model samp Kelkarles.

The observed tolerance influenced the calibration of the testing machine; therefore, the force was measured in either kilograms (kg) or kilonewtons (kN) and the samples were extended from both sides until failure. Additionally, to determine the maximum stress the samples could withstand before failure, this research conducted compressive strength measurements. The test procedure assessed the strength of the bamboo samples by measuring the cross-sectional area and its compressive strength to determine its tolerance to compression on a specific cross-sectional area.

During compression, both the force applied to the bamboo and the cross-sectional area were recorded. This procedure continued until failure and bamboo strength was determined by the compression sustained by the area at the point of failure. An equation was used to calculate the maximum compressive strength of the bamboo tested in this research.

Table 4

Codes for Optimisation Testing the Compressive Strength of Bamboos.

	Case study
Bamboo with top node	A
Bamboo with middle node	B
Bamboo with bottom node	C

Figure 13

Methodology Flowchart

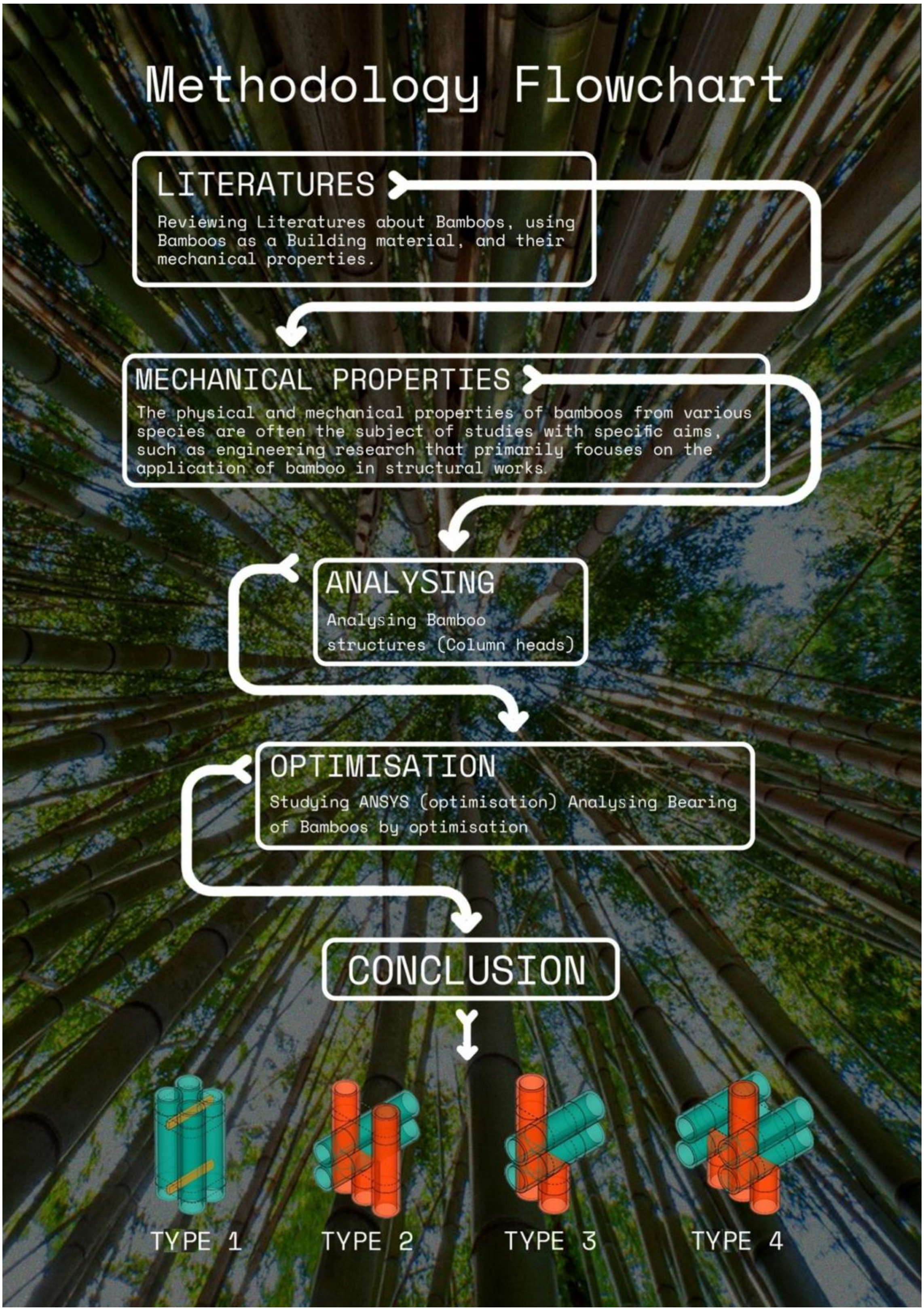
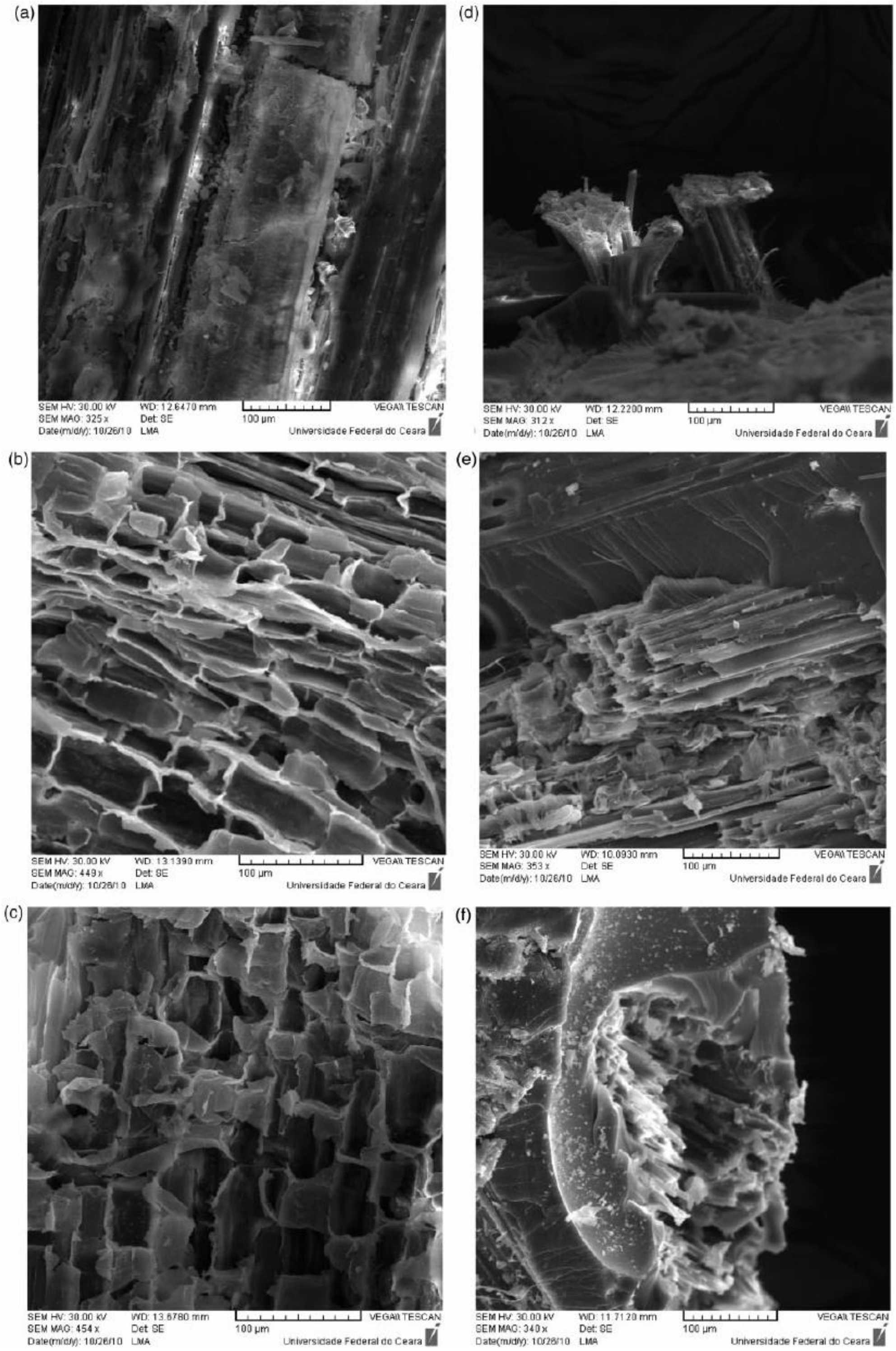


Figure 14

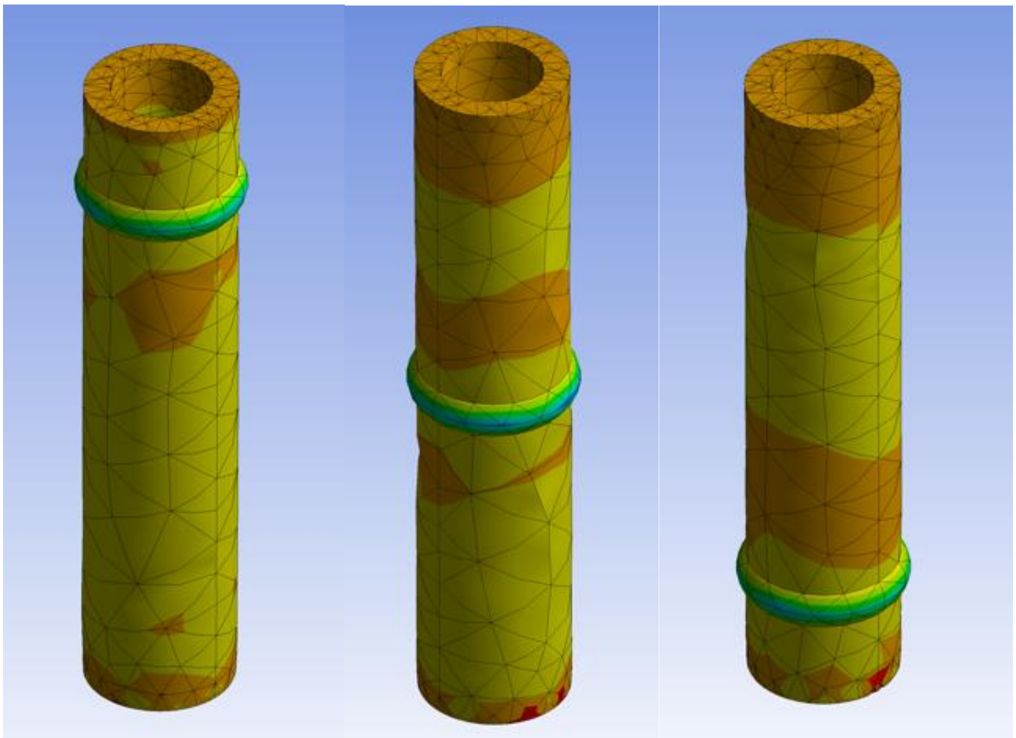
SEM Scanned Image of Bamboo



Note. From *Thermal and mechanical properties of biocomposites based on a cashew nut shell liquid matrix reinforced with bamboo fibers*, by A. Júnior, A. Barreto, D. S. Rosa, J. N. Maia, L. Diego, & S. E. Mazzetto, 2014, Composite Materials. Copyright 2014 by Composite Materials.

Figure 15

Features of Bamboos for Testing Optimisation



RESULTS AND DISCUSSION

When determining the compressive strength of bamboo, particularly when force is applied across the grain, a series of tests were conducted to assess how segmented bamboo performs with and without the presence of nodes (the joint areas of bamboo known as knots).

Figure 16 illustrates one of the key findings of this research that bamboo segments containing nodes exhibited superior load-bearing capacity than segments without nodes. Specifically, bamboo that was cut into three pieces for testing, and had a knot located in the middle section, demonstrated superior load-bearing performance.

In Case Study A (see Figure 16 and 17), where the bamboo segment's knot was positioned centrally, the distribution of weight was balanced effectively across both the upper and lower portions of the bamboo. This central node provided reinforcement, strengthened the bamboo's structure, and augmented its force resistance properties during testing. This experiment revealed that bamboo in this configuration can support a compressive load of 85.986 MPa (megapascals), which is a significantly higher value than bamboo specimens without a knot. Additionally, the test results reveal that bamboo segments with a central knot experienced comparatively minor structural damage. There was minimal evidence of breakage caused by the compressive force, indicating that the knot acted as a stabilising feature and prevented the bamboo from fracturing or failing under pressure

In most cases, only superficial cracks formed along the grain of the bamboo, running parallel to the axial direction, and did not compromise the overall integrity of the specimen.

Figure 16

The Optimisation Bamboo After Testing Compressive Strength

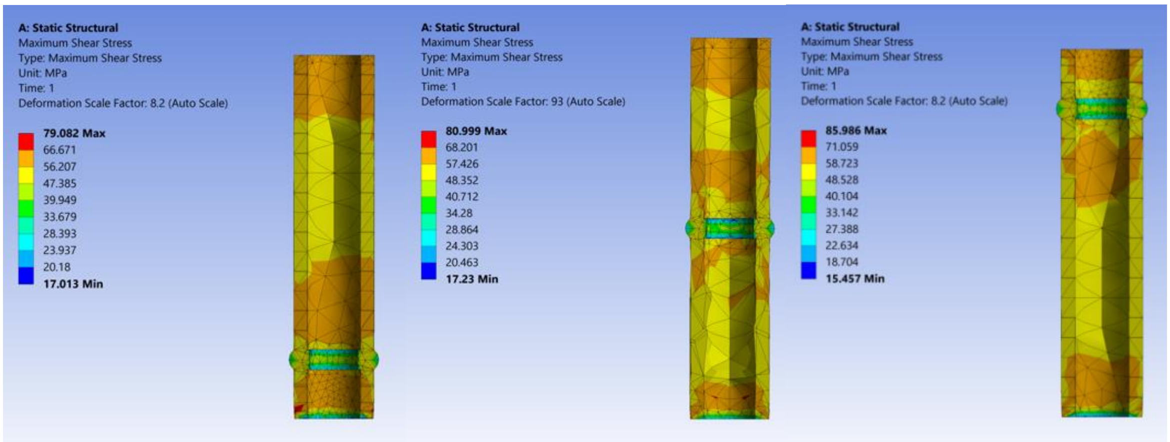


Figure 17

Case Study A

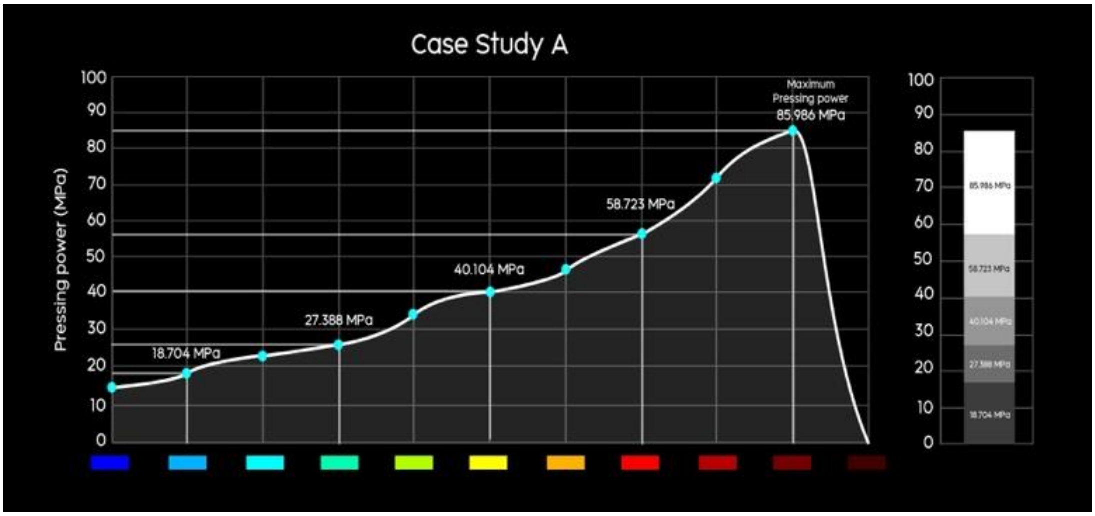


Figure 18

Case Study B

Figure 19

Case Study C

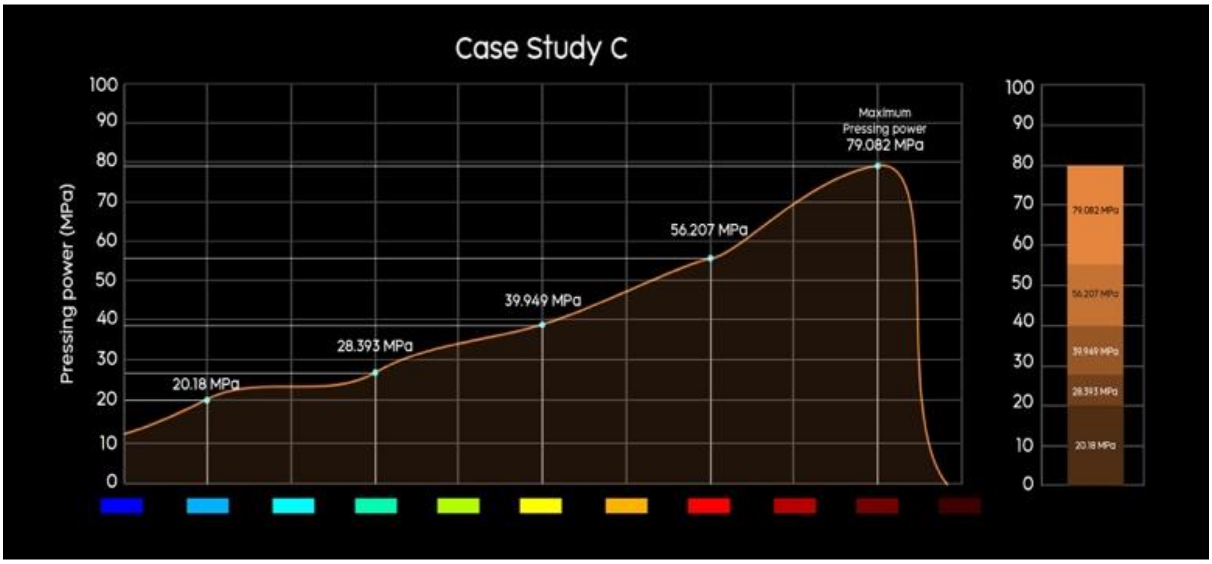
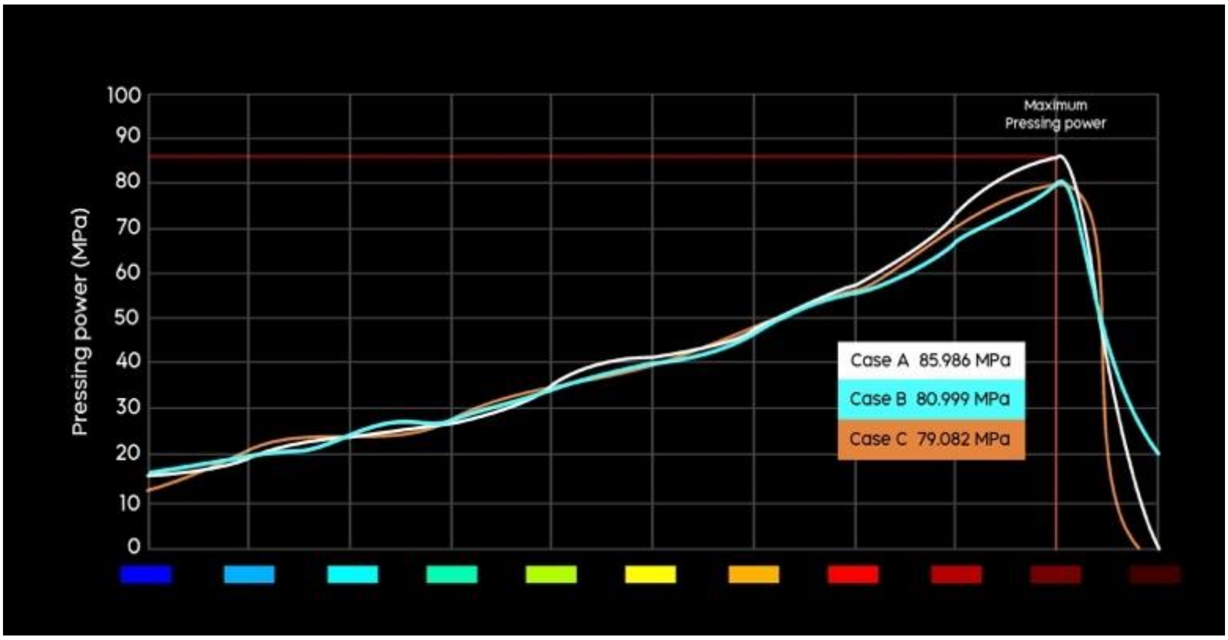


Figure 20

Overall Test Results of the Compressive Strength of the bamboo



In Case Study B (as shown in Figure 18), the bamboo sample supported a compression force of 80.999 MPa, which was a difference of 4.987 MPa when compared with the samples in Case Study A; additionally, the break was characterised by a distorted shape on the section without a knot.

This is illustrated by the graph that shows the weight supported and the figure that shows the distortion of the changing characteristics of bamboo when experiencing force on the part of the bamboo without a knot.

When analysing the final results of the three case studies involving perpendicular-to-grain compression assessments, the weight support comparison provided significant insights. The data revealed that Case Study C was able to support a compressive force of 79.082 MPa, which resulted in visible cracks and a noticeable distortion in the shape of the bamboo. The collated data signifies the comparatively high load-bearing capacity of bamboo in this configuration; however, it was less resistant to deformation and cracking when compared with other nodal configurations.

In Case Study C (as shown in Figure 19), the knot positioned at the bottom of the bamboo-segment was a significant factor. It functioned as a structural reinforcement point by dispersing the compressive force throughout the length of the bamboo which inhibited breakage and prevented any significant deformation of the lower part of the specimen. However, the applied force resulted in the stress being focussed on the section above the knot (in the upper section) which had to endure the majority of the load; therefore, the upper section displayed a noticeable reaction to the force and experienced deformation and cracking.

The bottom knot acted as a stabilising feature to prevent complete structural failure in the lower portion of the bamboo, thus enabling the bamboo to withstand a substantial amount of force before exhibiting any signs of damage. The presence of the knot not only enhanced the bamboo's overall capacity to support weight but also provided insights regarding the nodal contribution to the distribution of stress and the material’s resistance to failure under compressive loads. Despite the development of cracks in the upper portion, the knot at the base played a key role in maintaining the structural integrity of the sample and preventing catastrophic failure.

When comparing Case Study C to A and B, the results highlight the importance of the positioning of nodes within bamboo when considering structural applications (as shown in Figure 20).

The findings suggest that while bamboo without a central knot may still support significant loads, its overall stability and resistance to deformation are compromised when the compressive force is concentrated above a knot. This research emphasises the value of understanding how bamboo’s natural structure, particularly the positioning of its nodes, can affect its mechanical performance in construction. In summary, Case Study C demonstrated that bamboo can support a notable amount of force and the knot’s placement at the bottom of the specimen helped mitigate severe structural failure, especially in the lower regions. This insight has important implications for the use of bamboo in construction, as it highlights the need for strategic positioning of nodes to enhance the strength and durability of bamboo elements in load-bearing roles.

The strength of bamboo nodes (the joints located along the bamboo culms) plays a crucial role in making bamboo a highly effective building material, particularly in structural construction. Bamboo possesses excellent compressive, tensile, and shear strength, all of which contribute to its durability and the overall safety of structures. The nodes serve as reinforcement points that enhance the material's ability to withstand the various forces expected in construction applications.

The Importance of Nodes in Load Bearing

Bamboo

Bamboo nodes are structurally significant due to their thicker fibres and denser cell walls compared to the internodal sections, which results in greater resistance to the forces applied by the weight of a building or the tensile forces resulting from expansion or contraction. In a

construction context, the node acts as a reinforcement point, preventing cracking or buckling under pressure. Nodes are particularly useful in sections of bamboo used for load-bearing elements such as beams, columns, or main structural frameworks in buildings.

Bamboo in Structural Construction

In building construction, using bamboo with nodes in strategic positions improves the load-bearing efficiency of the structure. Placing a bamboo culm with a node at the centre of a column or beam significantly enhances its capacity to resist compression and tension, thereby increasing the overall durability of the structure. Additionally, this research posits that the use of bamboo containing nodes can minimise the risk of structural damage instigated by compressive or tensile forces which may occur when construction is in use.

Advantages of Nodes for Structural Durability

Compressive Strength: Bamboo nodes can withstand extreme levels of compressive force which makes them a valuable material for the construction of load-bearing structures such as columns and beams designed to support a roof or other primary structural elements. The presence of nodes strengthens the culm and prevents it from buckling or collapsing under the load. (as shown in Table 5).

Tensile Strength: Nodes improve the tensile strength of bamboo which enhances its resistance to breakage when undergoing stretching or pulling forces. This is a critical factor for structures which experience expansion or contraction.

Shear Resistance: The nodes amplify bamboo's shear resistance and enable the structure to resist forces that might cause it to twist or bend. This property is particularly useful in cases where the building is exposed to external forces such as extreme winds, earthquakes, or other environmental pressures.

In summary, bamboo nodes play an essential role in strengthening the structural performance of bamboo, especially when used in building construction. The unique composition of bamboo nodes enhances compressive, tensile, and shear strength, which is crucial for ensuring the overall durability and resilience of the material. By reinforcing these areas, the bamboo becomes more reliable when supporting substantial loads, which is crucial for key structural elements such as beams and columns. The strategic inclusion of bamboo with nodes in critical load-bearing areas significantly boosts the structural integrity of a building. Nodes act as natural reinforcement points by distributing the forces applied to the bamboo more evenly and preventing potential damage caused by compressive forces or bending. This property increases the lifespan of the structure and minimises maintenance costs, which makes bamboo a cost-effective and environmentally friendly building solution.

Additionally, bamboo's ability to withstand a variety of forces, combined with its lightweight nature and eco-friendly properties, makes it an increasingly popular material for sustainable architectural practices. Bamboo is prevalent in many parts of the world, grows rapidly, absorbs substantial quantities of CO_2, and requires minimal cultivation, all of which increase its appeal as a sustainable construction material. As the demand for environmentally friendly construction increases, bamboo is emerging as a highly viable alternative to traditional materials such as steel and concrete.

It should be noted that there were no failures at the nodes; indeed, the existence of a node significantly improved the fracture toughness. This property can be attributed to the distinctive distribution of vascular bundles in a tangential direction at the nodal regions. In the internodal region, the vascular bundles are arranged axially whereas in the nodal region, which contains bundles of coarser fibre, a higher volume fraction of fibres and three-dimensional woven fibre structures can be observed (Kelkar et al., 2023).

Analysing Optimisation of Bamboo Structures

The primary objective of the bamboo optimisation study concerned a comprehensive assessment of the load-bearing capabilities of columns and beams. There was a specific focus on identifying the nature of the damage and the precise locations of those areas which are most vulnerable to compression-induced failure.

To address the objective, this study conducted a comprehensive review of the existing literature regarding bamboo's mechanical properties, which provided a robust foundation for understanding bamboo's structural behaviour under compressive loads.

This analysis examined the compressive strength exhibited by a variety of nodal regions which are known to possess different mechanical properties (compared to internodal areas). These nodal areas are critical stress points caused by the natural structure of bamboo, which creates variations in strength and flexibility along its length. By assessing how bamboo behaves under compression at these specific locations, the study gathered valuable data regarding its overall performance in structural applications.

The data collected from these mechanical tests were subsequently used as inputs for optimisation via ANSYS software, which is a powerful simulation tool commonly utilised in structural engineering. ANSYS was used to create comprehensive models of bamboo columns and beams and simulated how these structures performed under diverse loading conditions. The study explored four different types of column and beam configurations to understand how variations in design affect load distribution, stress concentrations, and failure modes.

These simulations were invaluable in identifying a series of optimal configurations designed to enhance the load-bearing capacity of bamboo structures and increase their resistance to failure. Additionally, by simulating real-world conditions, the study provides insights regarding potential areas for reinforcing bamboo structures through design modifications or supplementary materials to further increase their durability and performance.

The findings of this optimisation process not only contribute to the understanding of bamboo's structural capabilities but also provide practical applications for its use in sustainable construction. By refining the design of bamboo columns and beams, this research bridges the gap between traditional building techniques and modern engineering practices and ensures that bamboo can be effectively utilised in contemporary architectural projects (as shown in Figure 21).

The investigation of the compressive strength of bamboo structures encompassing all four varieties of optimised columns and beams involved detailed analyses and required extensive data regarding the material properties and structural behaviour of bamboo.

This study aimed to refine the performance of bamboo under varying loading conditions by examining its compressive strength and durability. To ensure accuracy and precision in the simulation and analysis process, an exhaustive review of the relevant literature was conducted alongside experimental studies concerning bamboo structures.

The simulations were founded on comprehensively developed models designed to reflect practical contexts and reveal the structural behaviour of bamboo in various compressive conditions. These models established diverse compression conditions which facilitated an evaluation of the material's durability, tolerance, and potential failure points. The optimisation process allowed for an examination of several factors including bamboo's anisotropic characteristics, the influence of node positions, and how factors such as moisture content and age affected the overall strength of the material.

Additionally, the simulations were designed to enhance existing understanding regarding the structural functions of bamboo and initiate design improvements which would augment its compressive strength and resistance to long-term loads.

Table 5

Test Results regarding the Compressive Strength of the Bamboo - Case Study A, Case Study B, and Case Study C

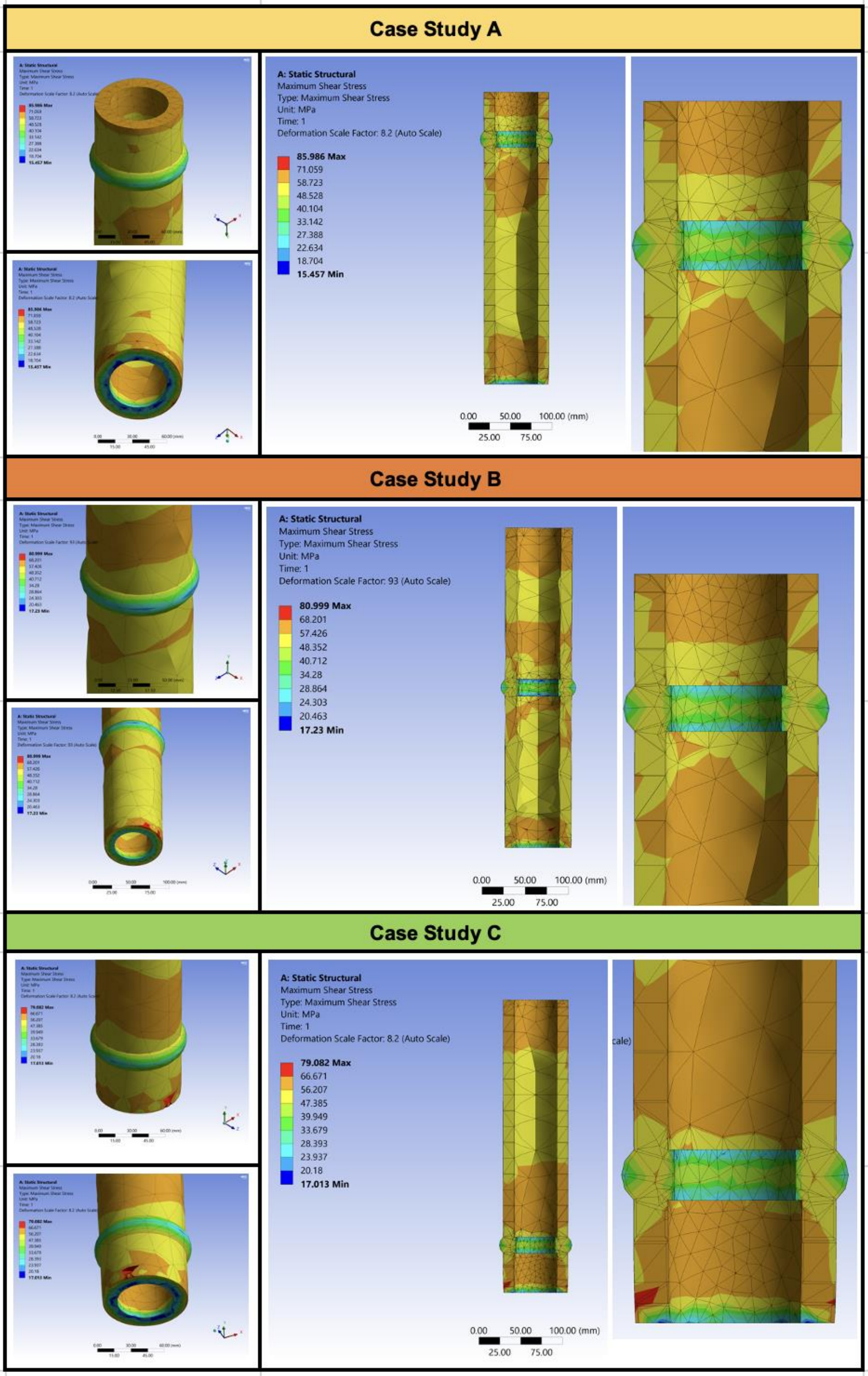
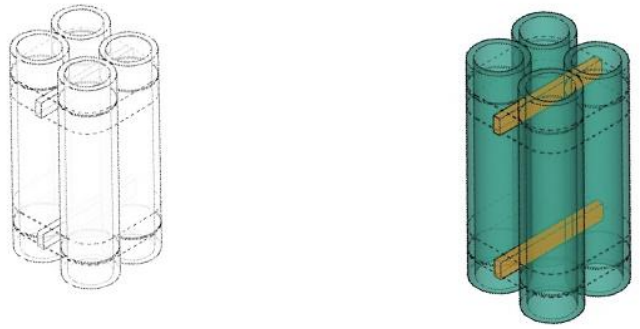
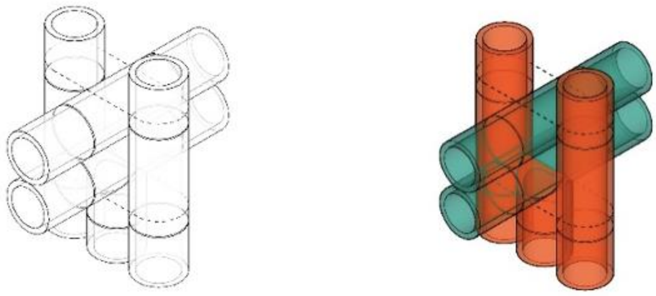


Figure 21

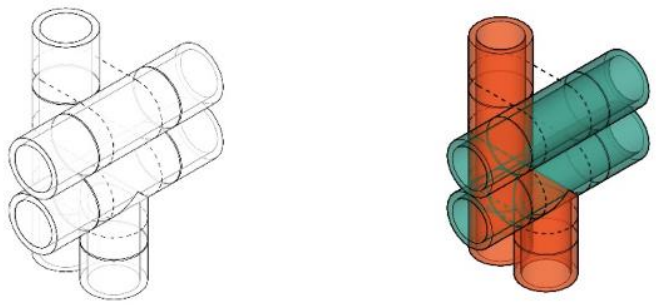
Types of Bamboo Joints



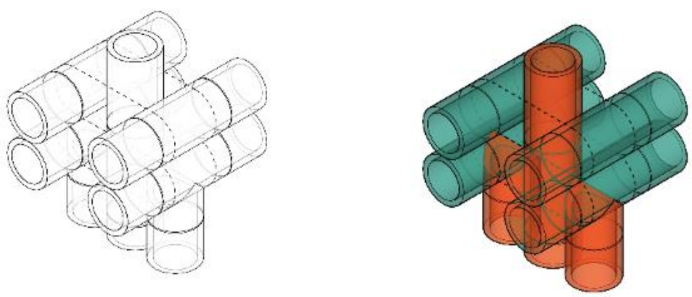
Type 1: This design utilises a columnar structure comprised of four three-inch bamboos arranged to support load-bearing.



Type 2: In this configuration, a column and beam structure is fashioned from three-inch bamboos. The setup incorporates double beams supported by three columns, with two columns joined together and the third serving as the indented support column beneath the beams.



Type 3: This column and beam structure is constructed from three-inch bamboos, where double beams are supported by two columns. One column is joined adjacent to the beams, while the other functions as the indented support column directly underneath the beams.



Type 4: Composed of three-inch bamboos, this structure features two sets of doubled beams connected to a central column. On each side, there is an individual indented bearing column beneath the beams providing support.

The optimisation focused on enhancing the inherent mechanical properties of bamboo and the overall structural system to increase load-bearing capacity in practical architectural applications. A key finding of the study was the identification of critical stress points which were typically located at the intersections where the structural components connect. These regions, particularly around nodes or joint areas, were found to be the most susceptible to damage, as they are required to tolerate the concentrated forces transmitted from other parts of the structure. By analysing these stress points and introducing reinforcement strategies, this study provided beneficial insights regarding the improvement of bamboo's structural integrity and longevity in construction projects. (as shown in Table 6, 7, 8 and 9) In conclusion, the optimisation of bamboo's compressive strength, along with the thorough data analysis and simulation models, has the potential to significantly enhance its application in sustainable architecture. The findings from this study lay the foundation for further exploration concerning the use of bamboo as a primary material in structural design, particularly in regions where environmentally friendly construction is a priority.

Table 6

Experimental Type 1

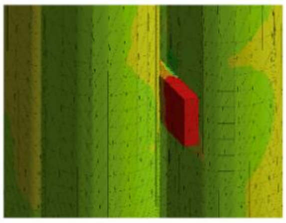
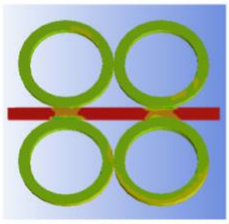
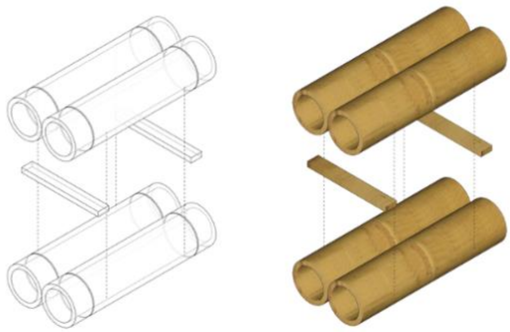
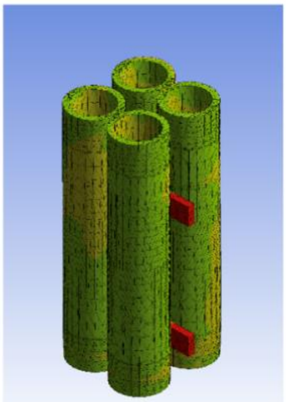
Experimental Type 1		
		 **Type 1 Damage:** Damage was attributable to the bearing of loads without the support of beams across all four columns, resulting in the bamboos being squeezed and compressed against each other at the points of connection. While no damage was observed on the bamboo surfaces, the compression points were identified as potential failure sites, where breakage or damage could occur, especially under conditions of excessive compression. Such damage has implications for the structure's overall strength and durability.
	 Note: Material setting in ANSYS was based on the literature review. Compression values were also set to ascertain damage.	

Table 7

Experimental Type 2

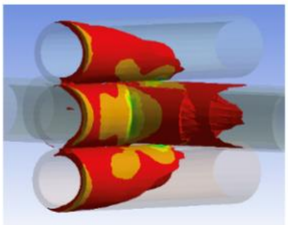
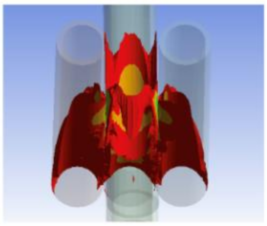
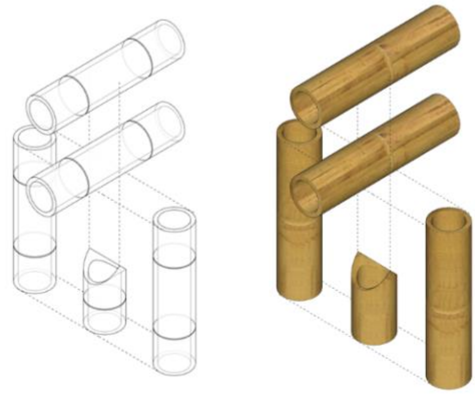
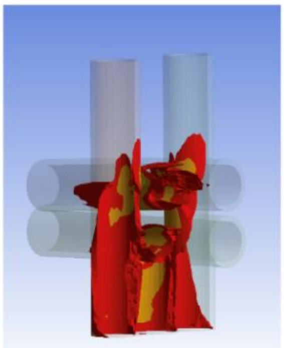
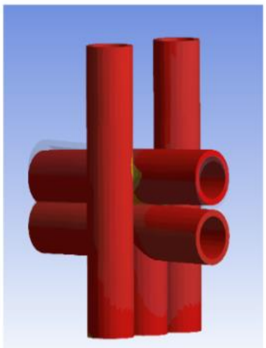
Experimental Type 2		
		
	 Note: Material setting in ANSYS was based on the literature review.Compression values were also set to ascertain damage.	**Type 2 Damage:** Damage to the lower beam resulted in stress being transmitted to the supporting columns underneath until the point of failure. Subsequently, this stress expanded laterally, affecting the columns on both sides through the exerted compressive forces.

Table 8

Experimental Type 3

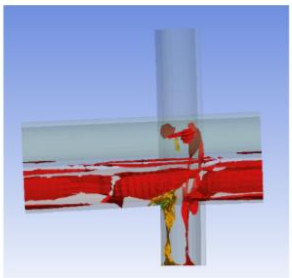
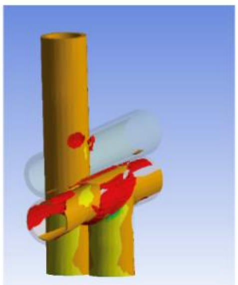
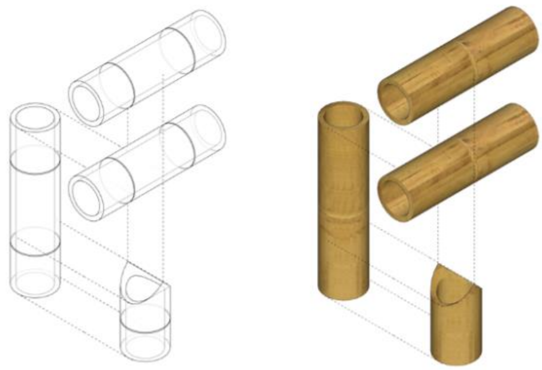
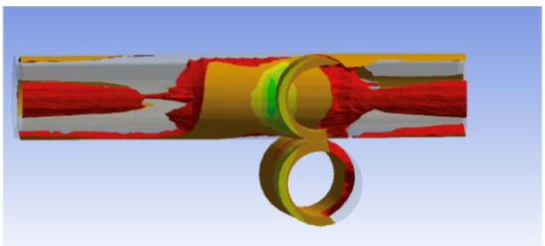
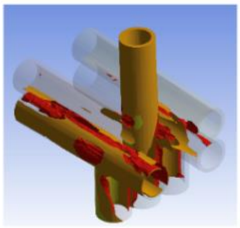
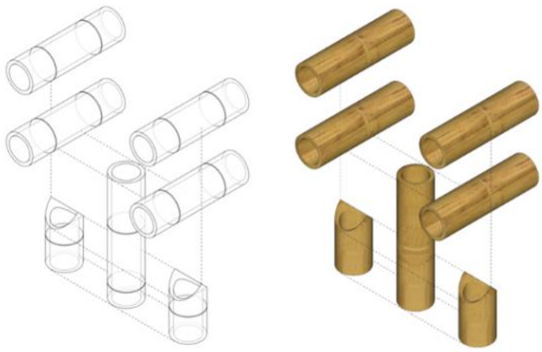
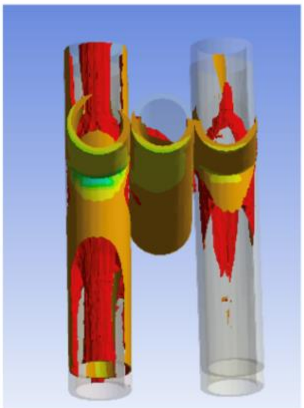
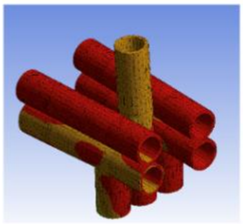
Experimental Type 3		
		
 Note: Material setting in ANSYS was based on the literature review. Compression values were also set to ascertain damage.		**Type 3 Damage:** Similar to Type 2, this category also exhibited significant damage at the lower column. The damage originated from the lower beam and extended to the lower column. In comparison, the adjacent column sustained only minor effects at the connection point.

Table 9

Experimental Type 4

Experimental Type 4		
		 **Type 4 Damage:** This type of damage was localised at the junctions between the beams and the columns, especially where the lower beams and load-bearing columns below intersected. The damage was consistent with the patterns observed in the previous types, occurring precisely at the bamboo connection points.
	 Note: Material setting in ANSYS was based on the literature review. Compression values were also set to ascertain damage.	

CONCLUSION

Bamboo has been a fundamental feature of construction since ancient times and its functions and designs have evolved continuously. Structures built from bamboo are resilient to variations in humidity and temperature. Several factors, including its rapid rate of growth, have made bamboo a primary contributor to structural sustainability. Moreover, its employment in construction is environmentally beneficial because it minimises the current dependence on steel and concrete whose production has a negative impact on the environment. Incorporating bamboo into structural designs promotes energy conservation, reduces greenhouse gas emissions, fosters sustainability, and reduces the environmental footprint of the construction industry and community.

- **High strength and flexibility**

Bamboo has excellent compressive and tensile strength while also being highly flexible. This makes it suitable for structures that need to withstand natural forces, such as earthquakes, which occur in Thailand's climate and geographic conditions.

- **Cultural and aesthetic significance**

Bamboo is intricately connected to Thai culture. Its use in building design reflects the beauty of traditional Thai arts and also helps to preserve and promote local artisanry.

- **Adaptability to local climate for vernacular in Thai architecture**

Bamboo enhances natural ventilation within buildings due to its ability to effectively absorb and evaporate moisture. As a result, structures made of bamboo maintain a cool and comfortable interior environment, which makes them suitable for Thailand’s tropical climate.

- **Carbon Sequestration**

One of bamboo's most important environmental benefits is its ability to sequester large amounts of carbon dioxide (CO_2) from the atmosphere. It absorbs CO_2 during its growth phase which mitigates the effects of climate change by reducing greenhouse gas emissions. Studies suggest that bamboo forests can absorb significantly more CO_2 than equivalent areas of traditional trees, making it an effective tool for carbon capture.

Eco-friendliness for Urban Areas

Bamboo is recognised for its ability to absorb carbon dioxide during its growth, which significantly reduces the amount of greenhouse gases in the atmosphere. Its rapid regeneration cycle and sustainable harvesting practices offer an environmentally friendly alternative to conventional materials such as steel or concrete. The production and construction phases associated with bamboo have a reduced environmental impact, which makes it particularly well-suited for urban development. Thailand possesses an abundance of bamboo, which is a natural resource and is considered highly suitable for use as a construction material for the construction of architecture that aligns with the country's hot and humid climate.

Throughout history to the present day, bamboo has been a crucial contributor to Thai culture, and this is evident in its increasing utilisation in traditional house construction.

This reflects a deep cultural connection, as bamboo's versatility is acknowledged and adapted to the specific conditions of each region in Thailand. Local artisans and building professionals, well-versed in regional materials and construction methods, contribute their expertise to the practical execution of the designs (Panin & Mokkhasmita, 2021).

This research regarding the mechanical properties of bamboo confirms that it is a robust, viable, environmentally friendly, and sustainable construction material. Its qualities of resilience, flexibility, and efficient compression tolerance were noted. The test results established that bamboo nodes exhibited strength and sustained no damage during testing. The maximum compressive strength for each node was as follows: top nodes achieved 80.999 MPa, middle nodes reached 85.986 MPa, and the bottom nodes produced a rating of 79.082 MPa. Notably, the areas prone to failure were located around the internodes. The practical tests concerning the mechanical properties of bamboo, which were subsequently optimised by ANSYS for columns and beams, revealed that damage sites in bamboo structures typically occurred at the connection points, which were consistently across all three models tested.

This study observed that damage occurred exclusively at the junction between the columns and the beams and that the columns maintained their structural integrity. However, the beams exhibited more extensive damage attributable to the inherent hollowness of the bamboo, which reduced their load-bearing efficacy relative to the cross-sectional areas.

Furthermore, bamboo is an eco-friendly material, particularly in urban environments. Due to its rapid growth and carbon-sequestering ability, it is therefore a highly sustainable option for urban construction projects. Bamboo absorbs significant amounts of carbon dioxide during its growth which mitigates greenhouse gas emissions. Additionally, using bamboo in place of traditional construction materials significantly reduces the environmental impact associated with the production and construction phases of steel and concrete.

The adaptability of bamboo in urban architecture is one of its most compelling features and enables it to be utilised in a diverse array of applications such as the structural frameworks of buildings and the intricate decorative elements that augment a building’s aesthetic value.

Bamboo’s natural strength and flexibility make it particularly suitable for use in urban environments where the demands for structural stability and innovative design are high. In the context of structural frameworks, bamboo can be used for load-bearing components such as beams, columns, and trusses, providing robust support while contributing to the visual appeal of the structure. Its lightweight nature allows for easier handling and assembly, reduces the overall construction time, and maintains the strength and durability of a structure.

Beyond its structural uses, bamboo is suited for decorative architectural elements such as wall cladding, screens, flooring, and furniture. In urban areas, where space is often at a premium, bamboo’s flexibility enables it to be used in a variety of creative ways that enhance both interior and exterior designs. Bamboo’s aesthetic qualities, warm tones, and unique texture provide an organic, natural feel that complements modern urban architecture and promotes a sense of harmony between the constructed environment and nature. In addition to its versatility, bamboo promotes sustainable growing, harvesting, and building practices. Bamboo is a fast-growing renewable resource; some species mature within three to five years, which makes it one of the most sustainable building materials available. Its rapid growth cycle allows for frequent harvesting without depleting the natural environment and ensures that bamboo can be used continuously without negative impacts on biodiversity or forest ecosystems. This promotes a circular economy whereby resources are reused and replenished to minimise waste and environmental degradation.

The cultivation and harvesting of bamboo can be conducted with minimal environmental impact, especially when compared to traditional building materials such as timber or concrete, which require considerable amounts of energy to produce and transport. Bamboo is defined as a low-maintenance crop because it requires minimal use of pesticides or fertilisers and can be developed in a variety of soils. In many regions, bamboo can be grown locally, which results in a minimal carbon footprint when compared with the long-distance transport of other construction materials, thereby making it the ideal material for eco-friendly developments in urban areas where sustainable and environmentally responsible construction is paramount.

Cities around the world are increasingly focusing on green building initiatives, where energy efficiency, resource conservation, and low carbon emissions are critical considerations. Bamboo meets these requirements by providing a construction material that is durable, adaptable, and aligns with the increasing emphasis on sustainability in urban development.

As urban population growth continues, the demand for sustainable construction materials increases; therefore, bamboo's ability to sequester carbon during its growth, coupled with its renewable nature, positions it as a key material in addressing the challenges posed by climate change and urbanisation. It allows architects and urban planners to design structures that are both functional and environmentally responsible, contributing to the development of greener, more sustainable cities. In conclusion, bamboo’s adaptability, sustainability, and aesthetic appeal make it an ideal material for a wide range of urban architectural applications. Whether used in large-scale structural projects or smaller decorative elements, bamboo offers a versatile solution that aligns with the values of modern eco-friendly urban development.

Utilising bamboo in construction supports the local economy and reduces its reliance on imported materials by minimising construction costs. Bamboo structures possess key characteristics that are ideal for Thailand’s environment, such as flexibility, durability against vibrations, and excellent ventilation, which contributes to cooler indoor spaces. Additionally, bamboo is an environmentally friendly material which absorbs carbon dioxide during its growth meaning that bamboo constructions can reduce greenhouse gas emissions and promote sustainability in architecture.

Therefore, the development and use of bamboo in Thailand’s construction industry is a viable option for environmental conservation, promotes sustainability, and supports the use of local materials in environmental architectural design.

Future Perspectives

Future research should examine the critical aspects of system design for the connection and load distribution of bamboo such as hybrid methods that incorporate steel with wood, the implementation of crosscheck engraving, and the application of screws in conjunction with crosscheck engraving techniques. Selecting appropriate methods of connection is paramount to improving the structural efficiency and extending the durability of bamboo constructions.

The rapid growth of bamboo and its adaptability to tropical climates make it an ideal material for use in urban architecture, particularly in regions with hot and humid conditions. Bamboo's ability to integrate into modern city planning and construction allows for a wide range of applications, from residential housing to eco-friendly commercial buildings.

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